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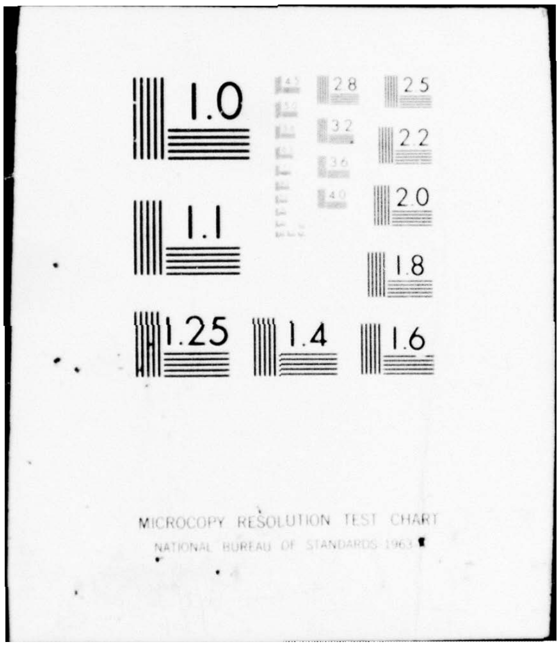
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TP 76-16

Coastal Changes, Eastern Lake Michigan, 1970-73

by

Richard A. Davis, Jr.

TECHNICAL PAPER NO. 76-16

OCTOBER 1976

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Prepared for

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This study concerns erosion of the bluff or edge of the terrace marking the landward boundary of the beach at 17 sites along a 250-mile segment of the east coast of Lake Michigan. Data were collected every 4 weeks for 3 years beginning in August 1970, during a period when mean monthly lake levels in Lake Michigan rose about 1.5 feet to record levels in the spring and summer of 1973.

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Bluff or terrace erosion was intermittent during the first 2 years, but universal during the final year, suggesting a critical lake level of about 580.0 feet, International Great Lakes datum, ~~(IGLD)~~ above which erosion on this coast generally occurs everywhere. For the 3-year period, net bluff erosion varied from 1 ~~cubic yard per foot~~ of beach front at two sites; one in the north and one in the south of the study area, to a maximum loss of 39 ~~cubic yards per foot~~ at the site on Big Sable Point. Erosion within the study area was intermittent over time periods equal to the survey interval (4 weeks), and local compared to distances between sites (about 15 miles).

cu yd/ft

Erosion increased with increase in lake level, although it is evident that lake level is merely a passive factor that permits waves to attack closer to the shore. Most erosion occurred during the late fall storm season when mean monthly lake levels were actually declining. Local factors, including bluff composition, shoreline orientation, occurrence of longshore bars, and protection from shore ice, appear to be important in determining erosion rates. Most of the sites in this study were away from the influence of coastal engineering structures.

An aerial photo study of these sites from 1938 to 1972 showed that long-term erosion is closely tied to lake level, and that sand terraces form rapidly in the backshore during periods of low water. Beach sediments appear to be locally derived and sand size does not show a clear relationship to the slope of the beach face.

1473B

PREFACE

This report is published to provide coastal engineers with bluff erosion data related to water level, storm occurrence, and bluff composition, useful for anticipating future effects from high water levels. The report summarizes the results of a 3-year reconnaissance study of bluff erosion, during high water levels, along a 250-mile segment of the eastern shore of Lake Michigan. Selected data from the first 2 years of this study were published in MP 10-75 by Davis, Fingleton, and Pritchett (1975). The work was carried out under the coastal processes program of the U.S. Army Coastal Engineering Research Center (CERC).

Professor Richard A. Davis, Jr., Western Michigan University, Kalamazoo, Michigan, was the principal investigator of the work done under CERC Contract Nos. DACW72-70-C-0037 and DACW72-73-C-0003. The report was prepared under the direction of Dr. C.J. Galvin, Jr., Chief, Coastal Processes Branch, Research Division. Dr. Craig H. Everts, Oceanographer, Coastal Processes Branch, was the CERC contract monitor.

Comments on this publication are invited.

Approved for publication in accordance with Public Law 166, 79th Congress, approved 31 July 1945, as supplemented by Public Law 172, 88th Congress, approved 7 November 1963.

JOHN H. COUSINS
Colonel, Corps of Engineers
Commander and Director

CONTENTS

TABLES

CONTENTS-Continued

TABLES

FIGURES

CONVERSION FACTORS, U. S. CUSTOMARY TO METRIC (SI) UNITS OF MEASUREMENT

U.S. customary units of measurement used in this report can be converted to metric (SI) units as follows:

Multiply	by	To obtain
inches	25.4	millimeters
	2.54	centimeters
square inches	6.452	square centimeters
cubic inches	16.39	cubic centimeters
feet	30.48	centimeters
	0.3048	meters
square feet	0.0929	square meters
cubic feet	0.0283	cubic meters
yards	0.9144	meters
square yards	0.836	square meters
cubic yards	0.7646	cubic meters
miles	1.6093	kilometers
square miles	259.0	hectares
acres	0.4047	hectares
foot-pounds	1.3558	newton meters
ounces	28.35	grams
pounds	453.6	grams
	0.4536	kilograms
ton, long	1.0160	metric tons
ton, short	0.9072	metric tons
degrees (angle)	0.1745	radians
Fahrenheit degrees	5/9	Celsius degrees or Kelvins[1]

[1] To obtain Celsius (C) temperature readings from Fahrenheit (F) readings, use formula: $C = (5/9)(F - 32)$. To obtain Kelvin (K) readings, use forumla: $K = (5/9)(F - 32) + 273.15$.

COASTAL CHANGES, EASTERN LAKE MICHIGAN, 1970-73

by
Richard A. Davis, Jr.

I. INTRODUCTION

Each time lake levels rise in the Great Lakes system there is apparently a corresponding increase in coastal erosion, and thus in property damage and loss. Coincident with these phenomena is an increase in concern by coastal residents and officials at all levels of government. Unfortunately, this concern generally diminishes as lake levels subside and coastal areas stabilize. As a result, there has been limited long-term planning or research associated with these periodic problems which directly or indirectly affect several million people.

A systematic monitoring of three beach locations in southeastern Lake Michigan was begun during June 1968 (Davis, 1972). These sites were surveyed and beach sediment was collected every 2 weeks. After more than a year of collecting these data it became apparent that coastal erosion was increasing and that this was coincident with rather rapid rises in lake level. These factors suggested that a widespread monitoring program along the eastern coast of Lake Michigan might serve as the basis for both determining the specific causes of coastal erosion and predicting patterns of erosion during periods of future lake level changes (see Davis, Fingleton, and Pritchett, 1975).

After nearly 2 years of profile surveys it became apparent that there were few, if any, patterns in the erosion rates, both with respect to time and space. It was necessary to expand the investigation to include the nearshore topography and a long-term aerial photo study. Nearshore topography was included because of the probable local effects in sedimentation caused by sandbars controlling the energy reaching the beach. The aerial photos were studied to determine if the locations being surveyed had reacted in a similar manner during previous periods of rising lake level.

This report summarizes the field observations and the aerial photo study, covering a 3-year period ending August 1973. The report supplements Davis, Fingleton, and Pritchett (1975) which contains a discussion of the first 2 years of profiling, a compilation of profile data for those 2 years, aerial photos of the 17 profile sites, and preliminary profile bench mark information.

1. General Coastal Geology and Morphology.

The study area is along the eastern coast of Lake Michigan between Point Betsie in the north and Lakeside in the south (Fig. 1; Table 1). This coastal area is underlain by Pleistocene glacial drift and characterized by reworked glacial drift which may take the form of dunes, lake or estuarine sediments, or beach sediments. No bedrock is exposed along the study area. Two aerial photos, along with pertinent geomorphological data

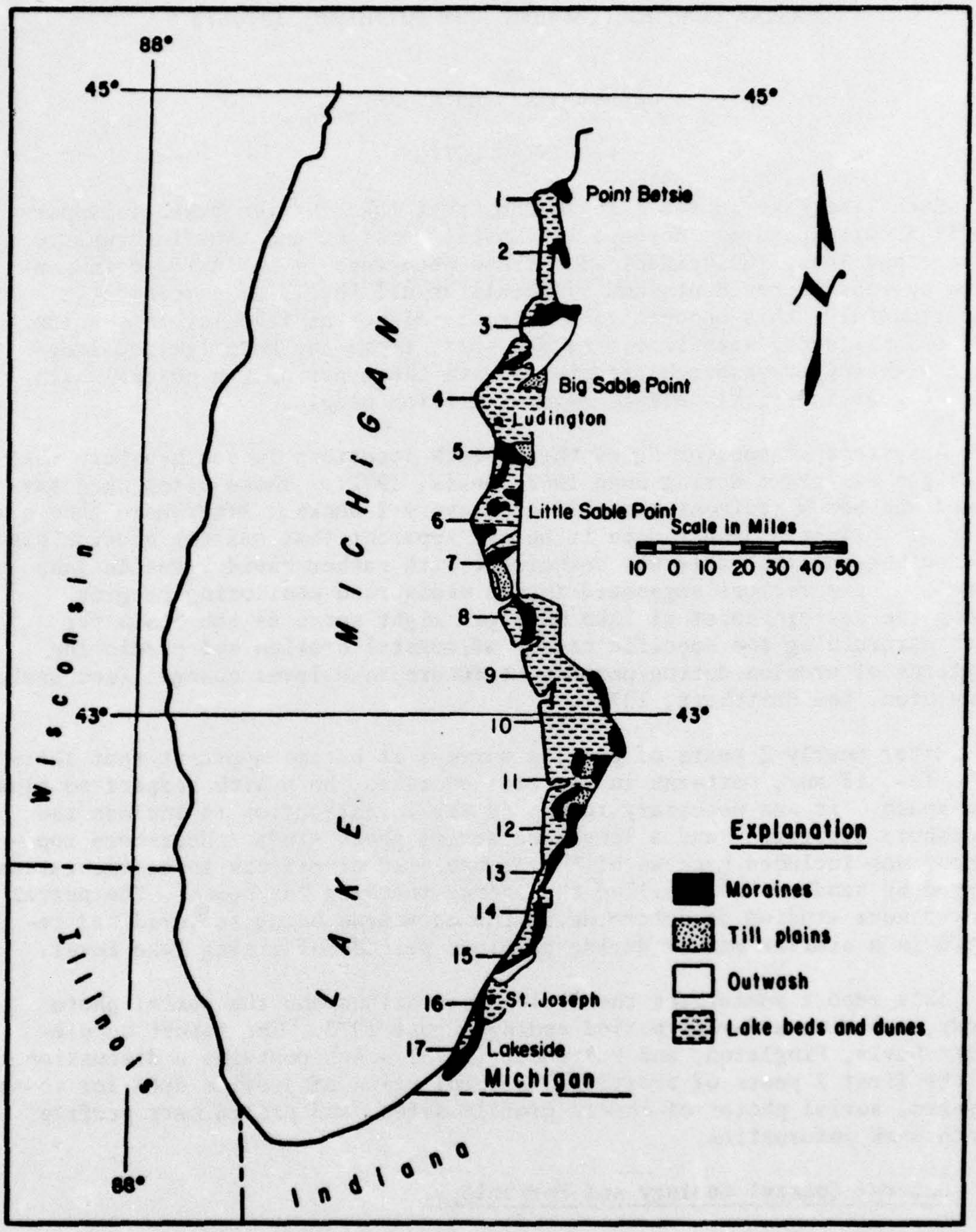


Figure 1. Index map showing profile sites and adjacent surficial geology along the eastern shore of Lake Michigan.

Table 1. Location of sites along profile line.

Site	Location
1	NW 1/2, sec. 4, T. 26 N., R. 16 W., about 200 yd south of old U.S. Coast Guard Station, Point Betsie, Mich.
2	Boundary between sec. 34, T. 25 N., R. 16 W. and sec. 3, T. 24 N., R. 16 W., at base of steep slope below roadside turnoff, between Benzie and Manistee Counties, Mich.
3	NW 1/4, SE 1/4, sec. 24, T. 22 N., R. 17 W., about 150 to 200 yd north of outlet of Bar Lake, Manistee County, Mich.
4	NW 1/4, SW 1/4, sec. 7, T. 19 N., R. 18 W., 150 yd south of lighthouse at Big Sable Point, Mich.
5	N 1/2, SW 1/2, sec. 23, T. 17 N., R. 18 W., just south of Summit Township Park, Mason County, Mich.
6	NE 1/4, SE 1/4, sec. 35, T. 15 N., R. 19 W., about 200 yd north of lighthouse, Little Sable Point, Mich.
7	NE 1/4, sec. 17, T. 13 N., R. 18 W., about 150 yd south of Claybanks Township Park, Oceana County, Mich.
8	SW 1/4, NE 1/4, sec. 24, T. 11 N., R. 18 W., just south of bend in road as it turns east around Duck Lake, Muskegon County, Mich.
9	SW 1/4, sec. 25, T. 9 N., R. 17 W., 300 to 350 yd south of Little Black Creek, in P.J. Hoffmaster State Park, Muskegon County, Mich.
10	Boundary between sec. 17 and 20, T. 7 N., R. 16 W., at Buchanan Street beach access, Ottawa County, Mich.
11	NW 1/2, sec. 21, T. 5 N., R. 16 W., about 300 yd south of James Street Public beach access, Ottawa County, Mich.
12	SW 1/2, NW 1/4, sec. 17, T. 3 N., R. 16 W., at Douglas Village Public Beach, Allegan County, Mich.
13	NW cor., sec. 31, T. 2 N., R. 16 W., 35 to 40 yd south of creek just below gravel road west of Glenn, Allegan County., Mich. (monitored since June 1968).
14	NW 1/4, SE 1/4, sec. 32, T. 1 S., R. 17 W., near north edge of Van Buren State Park, at base of large blowout, Van Buren County, Mich. (monitored since June 1968).
15	SW 1/4, NW 1/4, sec. 15, T. 3 S., R. 18 W., 50 yd south of steps at Hagar Township Park, Berrien County, Mich.
16	SW 1/4, NE 1/4, sec. 20, T. 5 S., R. 19 W., 300 yd north of Chalet-on-the-Lake, Stevensville, Berrien County, Mich. (monitored since June 1969).
17	SW 1/4, NE 1/4, sec. 19, T. 7 S., R. 2 W., at public access of Chickaming Township Park, Lakeside, Berrien County, Mich.

and bench mark locations, are given in Figures 6 to 22 in Davis, Fingleton, and Pritchett (1975). Table 1 of this report gives the location of the profile line as a whole, which may cover more territory than the bench mark locations in Davis, Fingleton, and Pritchett (1975).

Bluffs and terraces landward of the beaches are composed of moraines, till plains, outwash, lake beds, and dunes (Fig. 1) with the latter being most widespread. The beach and nearshore zones are composed primarily of sand with scattered gravel at most locations; however, there are a few sites where gravel is dominant. There are also a few sites where glacial till was temporarily exposed on the lake bottom in the surf zone or on the beach. This and other data (Davis, 1970), indicate that the thickness of the beach sand prism over the Pleistocene "bedrock" is quite thin. Resistivity surveys at several locations have shown the thickness to range from 3 to 10 feet at most of those sites where data are available.

Although the eastern Lake Michigan coast has a general north-south orientation, the orientation of the shoreline at the 17 profile sites (Fig. 1) is from N. 25° W. to N. 43° E., a range of 68°. The most prominent large-scale features are Point Betsie (profile site 1), Big Sable Point (profile site 4) and Little Sable Point (profile site 6), all of which occur in the northern part of the study area. Azimuths of each profile are given below:

Profile site	Azimuth
1	288°
2	281°
3	250°
4	277°
5	265°
6	277°
7	252°
8	246°
9	245°
10	259°
11	270°
12	280°
13	277°
14	295°
15	305°
16	296°
17	317°

The composition and morphology of the 17 profile sites reflect the varied nature of the eastern coast of Lake Michigan. There is no large sector of the coast which can be properly categorized into a specific type. Active dunes, stabilized dunes, till bluffs, or lake beds adjacent to the beach are found in all parts of the coast. As a result, the determination of a cause or causes is complicated by the general lack of uniformity of the coast in essentially all respects. Active dunes may be only a few tens of feet above lake level such as at Point Betsie or may

exceed 200 feet in height as in the southern part of the coast. Bluffs of clay till occur throughout (profile sites 5, 7, 10, 13, and 15), and may be capped in some places by dunes derived from lake sand.

There is one aspect of the coastal morphology that is rather widespread after a period of low lake levels. This is a sand terrace which is located behind the active beach and lakeward of the dunes, bluffs, or whatever comprises the coast (Fig. 2). The terrace is generally less than 10 feet above lake level and its width ranges from a few feet to more than 50 feet along the eastern coast. It is formed during low lake level periods when there is great accumulation of beach sediment. Onshore winds and occasional washover of waves pile sand in the backshore zone. This area is quickly stabilized by dune grass and shrubs so that in a period of less than 10 years, the terrace is fully developed and somewhat stabilized. Therefore, formation of these terraces is easily accomplished between periods of high lake level. The terraces are also quite susceptible to erosion and may be completely removed during high lake level.

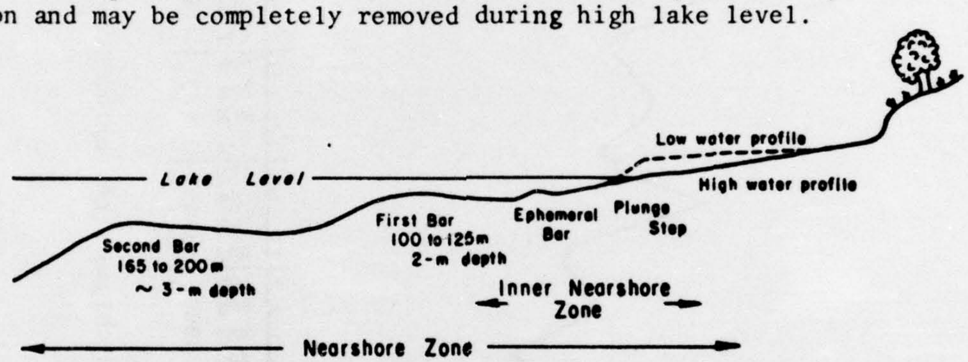


Figure 2. Generalized diagram across the beach and nearshore environment of eastern Lake Michigan.

2. <u>Lake Levels</u>.

Lake level is one of the few variables of this coastal environment which shows significant temporal change but is essentially uniform throughout the study area. Systematic monitoring of the lake level of the Lake Michigan-Lake Huron system has been in progress for more than a century. There is considerable fluctuation on both a long-term and short-term basis; long-period fluctuations range widely, but most periods fall between 9 and 13 years. During such an interval there may be a change of up to 4 feet in the mean annual level of the lake which is the result of fluctuating rainfall within the Lake Michigan-Lake Huron drainage basin. These rather large-scale and long-term fluctuations are quite significant in terms of coastal erosion.

There is also an annual lake level cycle about 1 foot in magnitude which is fairly predictable. It is a seasonal fluctuation resulting from changes in the water availability over 1 year's duration. Annual high levels are typical in July or August; the low is generally in February when there is little or no runoff due to freezing temperatures (Fig. 3). As spring melting and rains begin the lakes rise rapidly to the summer peak so there is a slight asymmetry to the annual curve.

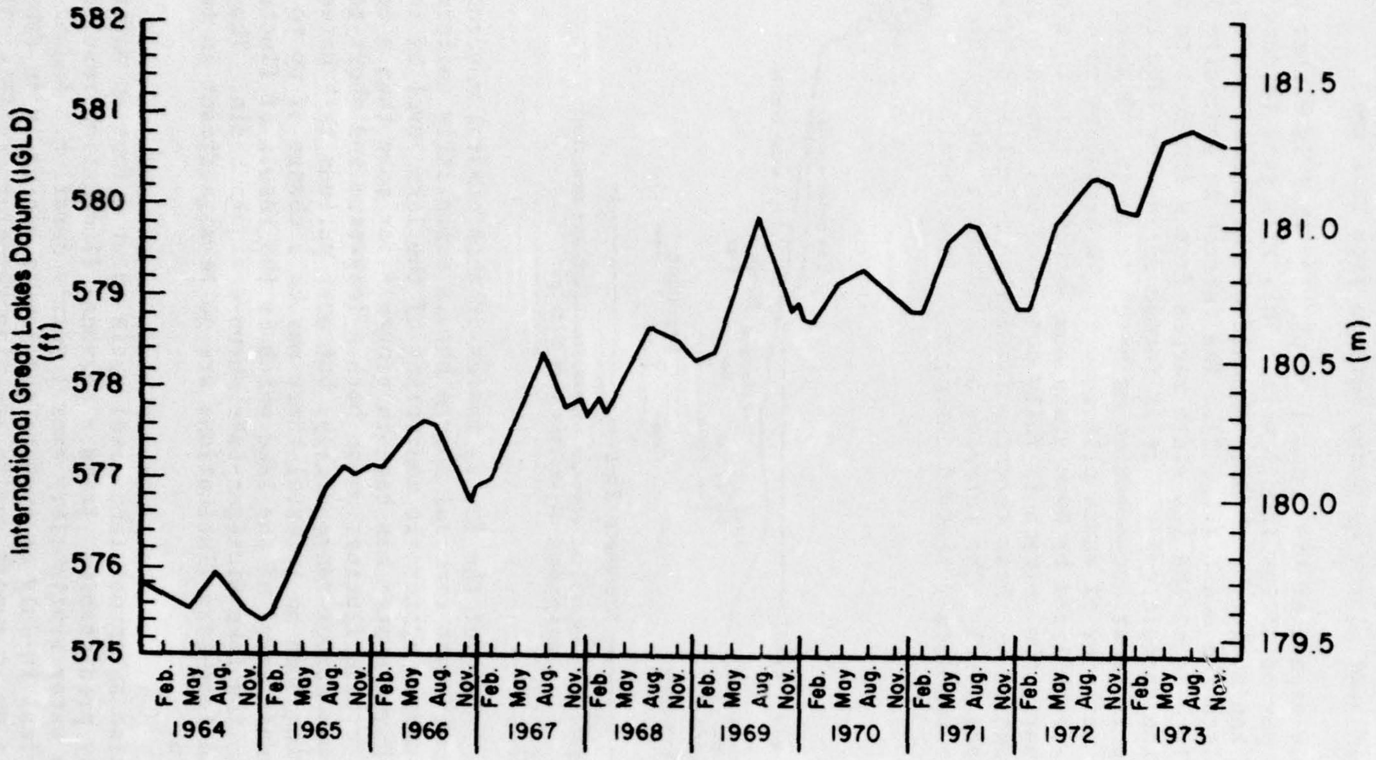


Figure 3. Quarterly level of Lake Michigan from period of alltime low (1964) to end of this study.

Slight and extremely short-term lake level changes occur in the form of astronomical tides and seiches. Both have periods of from a few hours to a day but are generally not factors in coastal processes because of their low amplitude. Storm surge or storm tides caused by intense weather systems and associated winds piling up water along the coast may be of significance. Such phenomena have been monitored with magnitudes in excess of 1 foot on eastern Lake Michigan (Fox and Davis, 1970b).

During the past few decades there have been periods of rather extreme lake level conditions at both ends of the spectrum. In the early 1950's, levels almost reached the alltime recorded high of the 1880's; the alltime low occurred during 1964. Since the alltime low there has been an abrupt increase in lake level so that the high level of 1952 has been surpassed. The rapid increase and its associated erosion are now coupled with much greater monetary losses because of the expanding use of the coast for private, public, and industrial development. As a result, millions of dollars are being lost each year. Much of this economic loss could be avoided through wise regulation of coastal zone utilization. This cannot be accomplished without a thorough understanding of the process-response mechanisms that are operating along the coast. This study should aid in achieving this goal.

3. Previous Studies.

Investigations of the eastern coast of Lake Michigan have been conducted for many years although the rate of activity has shown considerable variation. The dune areas in the southeastern corner of the lake which extend into Indiana were studied by Cressey (1928) who concluded that the longshore transport was predominantly to the south in that area. Beach sediments were analyzed by Pettijohn (1931) and Hough (1935). Coastal and nearshore morphology, particularly the longshore bars and troughs, was studied by Evans (1939, 1940).

With the exception of a geomorphologic study (Powers, 1958) and engineering investigations (Brater, 1950; Brater, Billings, and Granger, 1952), there was little research effort along the eastern coast during the next 20 years until the detailed analysis of nearshore sediments by McGeary (1964) and Cote (1967). In addition, there was concurrent work on the morphology and stability of the longshore bars and troughs (Davis, 1964; Davis and McGeary, 1965). More recent work on the geometry, sedimentary characteristics, and long-term motion of the longshore bars has been published by Saylor and Hands (1970) and Hands (1976).

A glaring omission from these research efforts has been the study of coastal erosion. There had been essentially none along this coast until the systematic survey of three sites in Van Buren and Allegan Counties began in June 1968 (Davis, 1970, 1972). The study of these three sites was expanded to produce the work by Davis, Fingleton, and Pritchett (1975) and the work described in this report.

Simultaneous with these studies have been similarly oriented projects by Brater and Seibel (1971) and Seibel (1972). Brater and Seibel dealt with some engineering aspects of erosion sites along eastern Lake Michigan; Seibel conducted a long-term aerial photo study of seven critical erosion sites on Lakes Michigan and Huron. Results from these studies are summarized in Davis, Seibel, and Fox (1974) and Seibel (1974). Great Lakes Basin Commission (1975) provides a later discussion of the recession rates in the study area.

II. BEACH MORPHOLOGY AND PROCESSES

Regardless of their location, beaches have a rather typical form and are subjected to similar processes. Primary differences from place to place include only the rate at which processes occur and the scale of the features involved. These topics have been discussed by Bascom (1964), King (1972), and Shepard (1972). The discussion of beach morphology and processes here is limited to eastern Lake Michigan.

1. Morphology.

The eastern Lake Michigan coast is characterized by sand dunes and bluffs of glacial drift. Lakeward of these features a low-lying sand terrace is typically developed; this feature may be absent or exist for only a few years from place to place. The terrace is commonly covered by grass and shrubs and is generally less than 10 feet above lake level. At any given time or place the terrace may terminate lakeward in a low bluff or may grade into the active beach without apparent topographic expression.

The backshore zone (Fig. 2) may be nearly horizontal or slope gently lakeward, depending upon the overall conditions at that time. During periods of accretion the zone is approximately horizontal; it slopes lakeward during periods of erosion. This variation in shape depends upon wave action on the beach and on lake level. As a result, there are both seasonal and long-term changes, with the long-term changes in lake level dominating. During periods of rising lake level, erosion dominates due to the combination of wave activity and encroachment of the strand line to the backshore zone. As a result, both the shape and the width of the beach are altered with minimal beach development during high lake level. There are sites on eastern Lake Michigan which have recently had no beach at all during high-energy periods of late fall when storms are common.

The foreshore zone also changes in response to lake level and storm conditions although there is only a minor change in its slope. In general, the foreshore is relatively steep (3° to 10°) in comparison to the backshore (Fig. 2). Erosion apparently steepens the slope of the foreshore and displaces it landward; accretion appears to reduce the slope. During prolonged periods of erosion the foreshore zone may comprise the entire beach.

Lakeward of the strand line and at the base of the foreshore slope is a plunge zone or plunge step. This is a small and abrupt topographic change with generally less than 1 foot of vertical relief over a horizontal distance of 1 to 3 feet. This feature is formed by the last breaking of

waves before runup on the foreshore, and is best developed under low-energy conditions. During periods of storm activity the plunge step may not be present as a topographic feature but its location may be indicated by an accumulation of coarse sediment, generally gravel, at that position on the profile.

Beyond the plunge step the profile slopes gently to the nearshore area where longshore bars and troughs are typically present. These bars are continuous, extending through the eastern Lake Michigan nearshore area; however, their position and depth vary (Hands, 1976).

The small ephemeral bar may be present, particularly just after storm conditions or during low-energy periods of the summer months. This bar is generally less than 100 feet from the strand line and has less than 3 feet of water over its crest. The bar will migrate shoreward during low-energy conditions and eventually weld to the beach (Davis, et al., 1972).

Most of eastern Lake Michigan contains two longshore bars although one to three are present at some locations. Although these bars are fairly stable (Davis and McGeary, 1965), they have been shown to move slowly in response to changing lake level conditions (Saylor and Hands, 1970). They are also rather continuous, based on aerial photos and field surveys. The migration, stability, and storm modifications of longshore bars are generally poorly known. Although the above-mentioned studies have attempted to monitor changes in these bars, there are as yet no good data on modifications that might occur during storms. It is apparent that there is little or no change between prestorm and poststorm profiles (Davis and McGeary, 1965; Davis and Fox, 1971). This situation could be quite different during a storm. The opinion of the author is that longshore bars are modified during intense wave activity but as the storm subsides there is a return to equilibrium conditions with no apparent changes.

2. Processes.

With the notable exception of significant astronomical tides, there is no general difference between beach and nearshore processes operating along eastern Lake Michigan and those on marine coasts. Studies of both types of coasts have confirmed this (Davis and Fox, 1972a; Davis, et al., 1972). Waves and currents are the dominant processes, and wind is of only minor significance, except in the formation of the foredune terrace. Currents are primarily of two types: Longshore currents and rip currents. Because of limited fetch in the Great Lakes, swell is not prominent in coastal processes.

There is an apparent cyclic nature of the processes operating along the eastern coast of Lake Michigan with the most prominent underlying causes being those of passing weather systems and in particular, fluctuations in barometric pressure (Fox and Davis, 1970b, 1971). In this latitude, weather systems generally move in a west to east path due to the prevailing westerly winds. As a low-pressure system (storm) approaches, the wind is from the southwest in the cyclonic system. This generates waves which approach the coast at an angle open to the north and thus generates northerly-flowing longshore currents (Fox and Davis, 1971). As the storm approaches the eastern coast of the lake there is an increase in

wind velocity, wave height, and longshore current velocity which accompanies the falling barometer. As the center of the storm passes over the coast there is typically an abrupt change in wind direction due to the flow of air on the trailing side of the cyclone. This produces strong winds from the northwest, and a change in the direction of wave approach and longshore current. Immediately after this shift in wind direction, the barometric pressure rises abruptly. This is characteristically the time of most intense energy imparted on the coast (Fox and Davis, 1971).

The above-described processes occur in a cyclic fashion with a period of 5 to 8 days. Intensity of the energy imparted to the beach varies, depending upon the change in barometric pressure and the proximity of the cyclonic system to the coast. Typically, storms of late fall and winter are the most intense although summer storms may also be severe (Fox and Davis, 1970b).

Associated with the waves and longshore currents are rip currents which typically reach their best definition and maximum velocity as storm conditions wane. These currents generally take the path of least resistance over saddles or lows in the crests of shallow longshore bars; however, under the proper conditions, rip currents may excavate large amounts of sediment and cut their own channels (Davis and Fox, 1972b). Rips are generally restricted to the area of the ephemeral sandbar or the inner bar if its crest is only 3 to 4 feet below lake level.

During storm conditions, winds in excess of 35 miles per hour, breakers of 3 to 4 feet, and longshore currents of 3 feet per second are not uncommon (Fox and Davis, 1970b, 1971, 1972). Extremely large quantities of sediment are moved under such conditions. During a summer storm in 1969, nearly 4,000 cubic yards of sand was removed from a stretch of beach 800 feet long (Fox and Davis, 1970b; Davis and Fox, 1971).

In addition to the erosion caused by storms there are processes where sediment is carried back to the beach during the low-energy periods between storms. Small waves break over the ephemeral sandbar or ridge and runnel system causing a landward migration of sediment. If sufficient time elapses between storms this sediment is carried all the way to the beach (Davis, et al., 1972). This process takes 5 to 10 days on the east coast of Lake Michigan.

III. METEOROLOGICAL DATA

1. Weather Patterns.

Generally, the weather (or more specifically, the wind) is the immediate driving force which generates the waves and currents that cause coastal erosion. The eastern Lake Michigan coast lies in the central part of the prevailing westerlies; thus, the weather is dominated by the west to east movement of low- and high-pressure systems. The westerlies and their cyclonic wind pattern are most prominent in the generation of intense physical energy which is ultimately imparted on the coast.

Low-pressure systems or cyclones generally move across or to the north of the eastern coast of Lake Michigan during the summer months and to the north during the winter. The most intense physical energy is generated by

the winter storms because of the generally higher winds. Because of the significance of low-pressure systems in the overall scheme of coastal processes and erosion, the number of low-pressure systems passing across Lake Michigan was obtained from the number of lows on daily weather maps of the National Weather Service (Table 2). These data indicate that late fall through early spring is the time when cyclonic systems pass most frequently. During the 3-year study period, the rate of cyclone occurrence was fairly constant. From 1970 to 1973, the annual number of cyclones was 36, 44, and 40, respectively, or an average of 40 cyclones per year which is close to the annual average of 43.2 cyclonic systems passing over the Lake Michigan area between 1938 and 1970 (Seibel, 1972).

Because of the general consistency in the total number of storms that pass through the area annually, and the relative uniformity in the seasonal nature of the distribution of cyclonic systems during each year, this is not an important variable with respect to the annual or long-term periodicity of coastal erosion. However, the above discussion of cyclonic systems does not consider the intensity of the storms which is a variable that must be considered.

Typically, the most intense storms develop during late fall and winter; however, because of the winter ice cover, November and December storms are most effective in coastal erosion. Although there may be extremely intense storms during summer, they are not common. One such storm in July 1969 caused severe erosion on the southeastern coast of Lake Michigan (Fox and Davis, 1970b).

Fetch is a limiting factor in wave development in Lake Michigan. The relatively shallow nearshore area also causes waves to break at a considerable distance from the beach. As a result, breakers rarely exceed 5 or 6 feet, although local residents and newspapers have reported 12- to 20-foot waves. Because of the elongate nature of the lake in a north-south direction, there is a considerable fetch difference between the north and south end of the lake with respect to the two primary wind directions. For example, winds from the southwest have a long fetch toward the northern part of the study area but the fetch is short for those locations in the southern part; winds from the northwest cause the opposite situation.

Wind velocity and direction data were obtained from the U.S. Weather Bureau at the Muskegon County Airport, Muskegon, Michigan. This station is located nearly 3 miles from Lake Michigan on a flat plain approximately 40 feet above lake level. Although trees are present on the lake margin, there are none about one-half mile immediately adjacent to the weather station. Because of the station's central location along the eastern coast of Lake Michigan and the absence of any other first-order weather stations nearby, all data were compiled from this location. Wind roses for each of the 3 years show the expected similar patterns with two modes, one from the southwest and one from the northwest (Fig. 4). This pattern is similar to that found for a 10-year period from 1960 to 1969 (Seibel, 1972).

Climatological data show that the prevailing winds are from the southwest and the predominant winds from the northwest. The predominant winds are generated by the trailing side of the cyclonic system as it passes over Lake Michigan.

Table 2. Cyclonic weather systems across Lake Michigan.

Year	Aug.	Sept.	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	June	July	Total
1970-71	0	2	1	3	6	5	4	6	2	2	3	2	36
1971-72	2	3	3	4	5	3	6	4	5	6	2	1	44
1972-73	4	2	1	4	6	2	5	4	3	5	2	2	40
Total	6	7	5	11	17	10	15	14	10	13	7	5	120

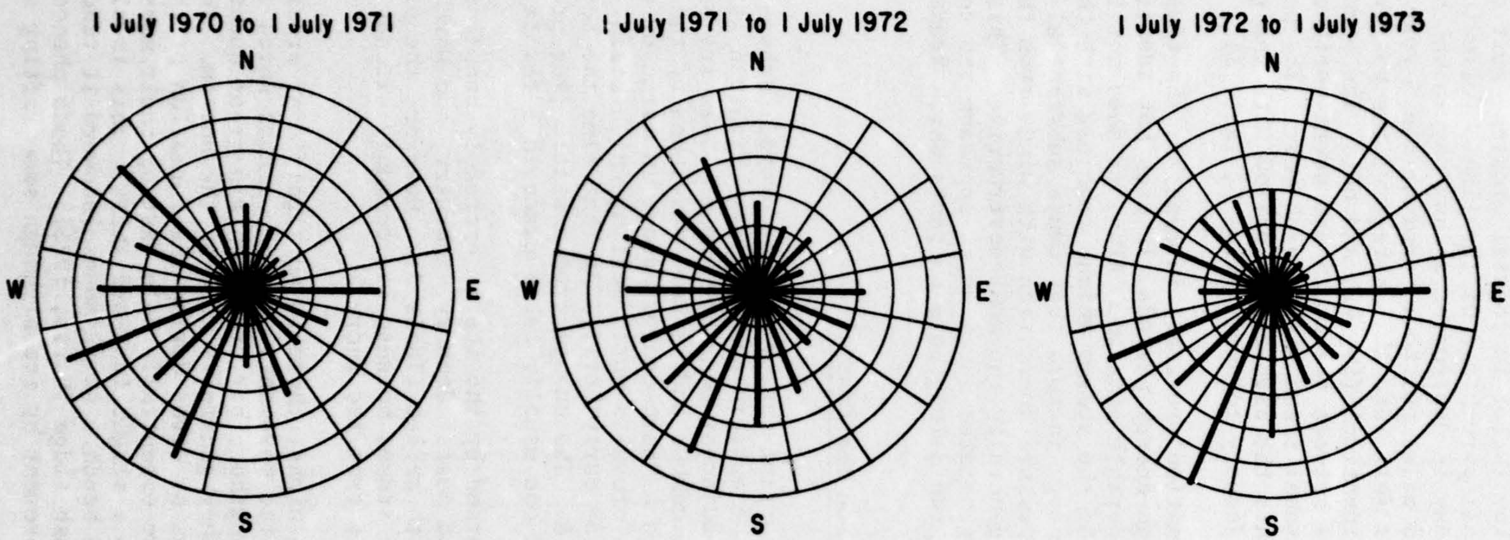


Figure 4. Wind rose diagrams for the study period. Each concentric circle represents 2 percent (from the U.S. Weather Bureau, Muskegon, Michigan).

Since storms are a key factor in coastal erosion, most coastal erosion occurs during only a small percentage of the time. Following the method of Seibel (1972), a storm day is designated as any day in which the wind velocity averages at least 15 miles per hour. During the 3-year study period, 16.7 percent of all days fell into this category; the yearly totals of storm days were nearly identical (59, 62, and 60). The mean wind direction for storm days lies between the south and north-northwest direction. There is an obvious seasonal trend within each year. The period of November to May represents the high-energy period with the greatest storm day concentration from January to April (Fig. 5, Table 3).

Although this information provides, in general, the temporal and directional nature of the high-energy periods, it does not identify the specific storms that cause considerable erosion. Also, it does not indicate the duration and intensity of the storms which, combined with the "direction," provide the important energy factors that cause substantial erosion. The slow-moving, deep low-pressure depression with winds from the north-northwest or north are generally the most destructive. This direction provides a long fetch and generates waves which approach the coast at a substantial angle, causing rapid longshore currents which transport much sediment.

2. Ice and Its Effects on the Coast.

One of the most important factors in the overall scheme of coastal processes and erosion on the eastern coast of Lake Michigan is the ice that forms on the beach and adjacent nearshore zone. This ice generally begins to accumulate in late December and is well developed by the first of the year. The coast is then a "zero-energy" coast in terms of coastal processes. This situation prevails until melting which begins in early March and ends in late March or early April. At that time the beach resumes its extremely dynamic nature. The change from a static (ice-protected) coast to a completely dynamic one usually takes place in a few days.

The protection afforded by the ice is extremely beneficial because it occurs when it is needed most. January, February, and March have the most storm days of any 3-month period (Table 3). However, the presence of the ice totally negates the storms because ice commonly extends about one-quarter to one-half mile from the shore.

Contrary to some opinions, there is no significant erosion to the coastal area caused by ice movement. The ice ridges which form on the landward side of the longshore bar crest contain great quantities of sand and are so thick that they generally rest on the bottom. The sand is incorporated in the ridges by waves during the formation of the ridges (Davis, 1973). These ridges are essentially held fast by their mass although strong onshore winds may cause a slight landward shift. This is also true for ice on the foreshore of the beach. As it moves landward it tends to form a small anticlinal ice-push ridge (Davis, 1973). These phenomena represent the bulk of sediment movement by ice although some rafting also occurs.

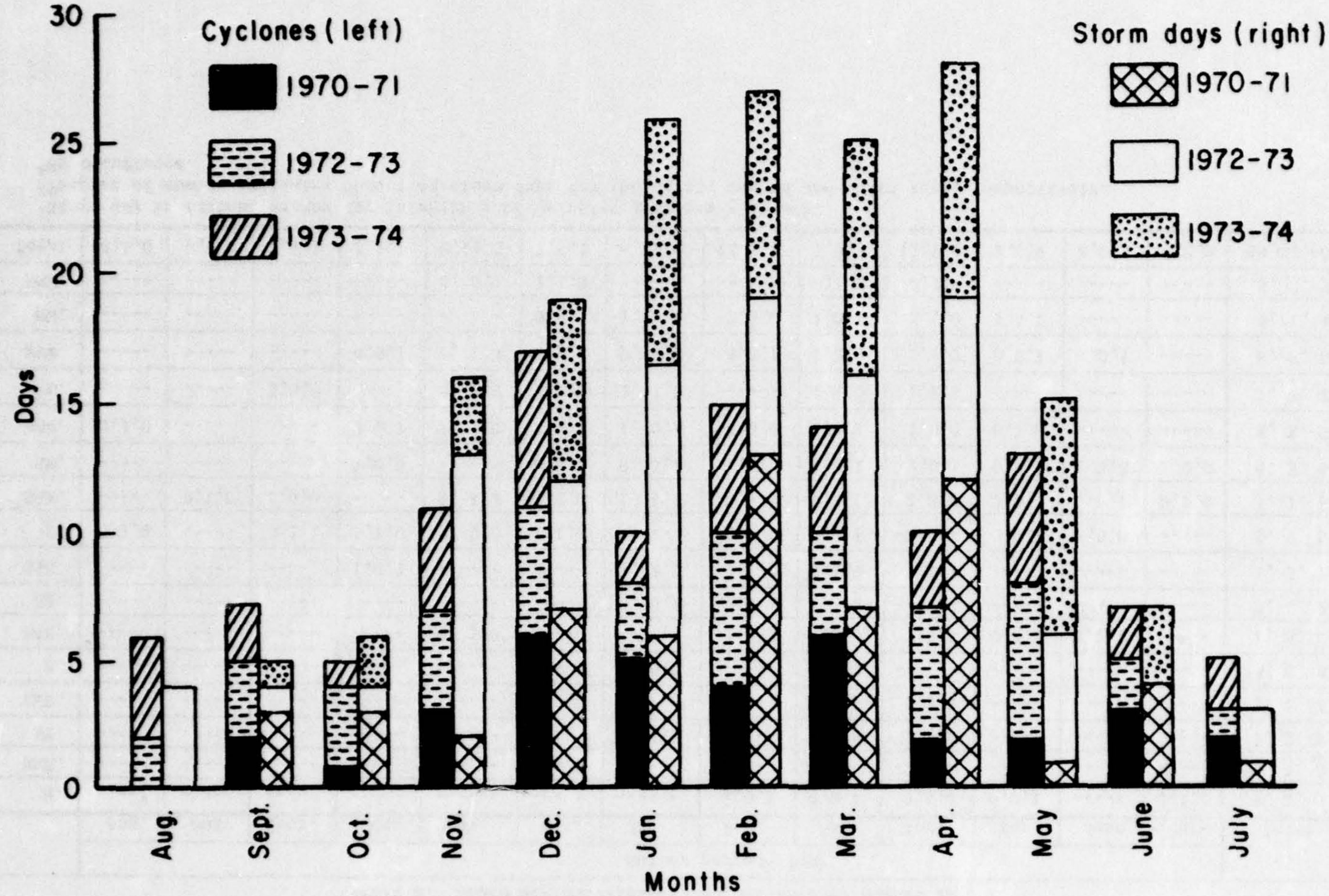


Figure 5. Number of cyclones and storm days during each month of the 3-year study period.

Table 3. Storm day occurrences, August 1970 to August 1973[1].

Avg. wind direction blowing from indicated compass point.	Survey period[2] (mo)													Total
	Aug.	Aug.	Sept.	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	June	July	
N.	-----[3]	-----	-----	-----	------	-----	------	1,0,1	0,0,1	0,1,0	0,0,1	-----	0,1,0	1, 2, 3
NNE.	-----	-----	-----	-----	------	0,1,0	------	------	-----	------	-----	-----	-----	0, 1, 0
NE.	-----	-----	-----	-----	------	-----	0, 1,0	------	-----	1,1,0	-----	-----	-----	1, 2, 0
ENE.	-----	-----	-----	-----	------	1,0,0	------	------	-----	0,1,1	-----	-----	-----	1, 1, 1
E.	-----	-----	-----	-----	------	-----	1, 0,0	------	2,0,0	------	-----	-----	-----	3, 0, 0
ESE.	-----	-----	-----	-----	0, 1,0	-----	------	1,0,2	0,0,3	0,0,3	0,2,1	0,0,1	-----	1, 3,10
SE.	-----	-----	-----	-----	------	-----	0, 0,1	0,0,1	-----	------	-----	-----	-----	0, 0, 2
SSE.	-----	-----	-----	1,0,0	------	-----	0, 2,0	o,1,0	0,1,0	0,1,1	-----	-----	-----	1, 5, 1
S.	0,2,0	-----	0,1,1	1,1,0	0, 2,0	1,1,0	------	0,0,2	0,0,1	------	0,0,1	1,0,0	-----	3, 7, 5
SSW.	-----	0,1,0	2,0,0	-----	0, 1,2	1,0,0	1, 1,1	0,3,1	0,2,1	2,0,0	0,2,2	1,0,1	0,1,0	7,11, 8
SW.	-----	-----	-----	1,0,0	------	0,0,2	0, 3,1	1,0,0	1,0,1	1,0,1	0,0,1	1,0,0	1,0,0	6, 3, 6
WSW.	0,1,0	-----	-----	0,0,1	1, 3,0	0,1,2	1, 0,3	4,0,0	1,2,1	1,0,0	0,1,0	-----	-----	8, 8, 7
W.	-----	-----	1,0,0	-----	0, 3,0	2,0,0	2, 2,1	------	1,1,0	1,1,1	-----	-----	-----	7, 7, 2
WNW.	-----	-----	-----	0,0,1	1, 1,0	1,1,2	0, 2,2	4,2,1	0,2,0	1,1,0	0,0,1	1,0,1	-----	8, 9, 8
NW.	-----	-----	-----	-----	------	0,0,1	1, 0,0	2,0,0	2,0,1	3,1,0	1,0,2	-----	-----	9, 1, 4
NNW.	-----	-----	-----	-----	0, 0,1	1,1,0	------	------	0,1,0	2,0,2	-----	-----	-----	3, 2, 3
Total	0,3,0	0,1,0	3,1,1	3,1,2	2,11,3	7,5,7	6,11,9	13,6,8	7,9,9	12,7,9	1,5,9	4,0,3	1,2,0	59,62,60

[1]Storm day is defined as any day in which wind velocity averages $\geq$ 15 m/h.
[2]Triplet of number indicates number of storm days for the first, second and third year, respectively.
[3]No occurrence.

Melting of the ice is such that the ice sheets between the ridges and between the shore and the first ridge melt first. This presents a series of two or three ice ridges with open water between them. However, the ridges are still an effective barrier to wave and current energy. Breakup of the ridges, their subsequent removal, and melting are generally caused by storms. As a result, the beach may go from a zero-energy situation to a high-energy condition in a matter of a few days.

IV. METHOD

1. Profiling Method.

Profiling techniques are the same as those used for data reported by Davis, Fingleton, and Pritchett (1975); the following description is adopted from that report. The technique for measuring beach profiles is essentially that described by Emery (1961). The only equipment used is a pair of wooden stakes, 5 feet long and graduated at 0.1-foot intervals. The method requires at least two persons although it is desirable to have a third to record the data.

The survey was started at a bench mark using a metal pipe or wooden stake. The height of the stake above ground level was noted to recognize any accumulation or erosion to the surface adjacent to the stake. The direction of the profile (perpendicular to the beach) was visually approximated. Horizontal distances were measured with a 5-foot stake, and topographic changes less than 5 feet in horizontal distance were recorded to the nearest foot. Vertical changes were determined by lining up the horizon with the top of the lakeward stake and noting the difference to the nearest 0.05 foot on the landward stake. Horizontal changes were referenced to the bench mark; vertical measurements were referenced to the lake level at the time of the first survey which was 579.4 feet, International Great Lakes Datum (IGLD). Measurements were made by a hand level in case of fog or ice ridges which could prohibit sighting of the horizon.

2. Profiling Format and Dates Visited.

Each of 17 beach sites was visited once every 4 weeks, and the routine for data collection remained fairly constant. The basic format was as follows:

(a) Location of the monument and determination of the need of an auxiliary stake if the permanent stake was in danger of removal by erosion.

(b) Profiling the beach to the plunge step, if possible, using the technique by Emery (1961). During late fall storms it was sometimes impossible to profile to the desired terminus.

(c) As each profile was surveyed, notations were made of topographic and sedimentologic features on the profile. These included small wave-cut features, ridge and runnel development,

gravel accumulation, heavy mineral concentrations, and driftwood or other debris.

(d) Color slides were taken of all sites during each visit, mostly from about 100 feet south of the profiles. The slides recorded the overall character of the site at each visit.

Dates of the visits to the 17 sites, spaced at approximately 4-week intervals, are listed in Table 4.

3. Data Limitations.

An office and field analysis of the Emery (1961) method of surveying (Czerniak, 1973) indicated a possibility of cumulative error that could result in the seaward end of the measured profile being displaced up to 1 foot vertically from the actual profile. There was also a problem reestablishing some of the bench marks which had disappeared between surveys. For these reasons, only gross changes could reliably be analyzed, and only those changes on the landward end of the profile would be sufficiently accurate to quantitatively evaluate. Therefore, this report is limited to an evaluation of the recession of the dune or bluff, although beach change trends are discussed for particular sites.

V. BEACH PROFILE CHANGES

The following discussion on each of the 17 beach sites is based on the profile surveys and color slides described previously. In the discussions the terms *terrace recession*, *bluff recession*, and *erosion* refer to the amount of horizontal retreat of the steep part of the profile that lies landward of the active beach. The term *erosion* is used to denote removal of sediment from the profile; *accretion* indicates addition of sediment to the profile. Additional information, vertical and oblique photos, bench mark locations, and geomorphology of the 17 profile sites are available in Davis, Fingleton, and Pritchett (1975).

1. Change at Each Location.

a. Profile Site 1. The beach is typically composed of much pebble and cobble-gravel with imbrication common. Low-lying vegetated dunes which contain numerous blowouts are adjacent to the beach. The U.S. Coast Guard station at Point Betsie and associated seawalls are located about one-quarter mile north of the site.

During the first year of study there was little change in overall beach configuration. A small ridgelike berm of gravel was present through most of the year. The seaward face of the low-lying dunes eroded 7 feet during the fall of 1970, without a corresponding change in beach position. This indicates that the beach recovered from storm erosion in less than the 4-week period between surveys. Erosion during July 1971 caused the usual concentration of heavy minerals in the backshore area.

Table 4. Profiling dates by survey number.

Survey number	1970-71	Survey number	1971-72	Survey number	1972-73
1	3 to 5 Aug. 70	14	2 to 3 Aug. 71	27	29 to 30 July 72
2	28 to 29 Aug. 70	15	26 to 28 Aug. 71	28	25 to 26 Aug. 72
3	26 to 27 Sept. 70	16	24 to 26 Sept. 71	29	29 to 30 Sept. 72
4	24 to 25 Oct. 70	17	22 to 24 Oct. 71	30	20 to 21 Oct. 72
5	21 to 22 Nov. 70	18	19 to 20 Nov. 71	31	18 to 19 Nov. 72
6	18 to 20 Dec. 70	19	20 to 21 Dec. 71	32	28 to 29 Dec. 72
7	15 to 17 Jan. 71	20	15 to 17 Jan. 72	33	13 to 14 Jan. 73
8	12 to 13 Feb. 71	21	12 to 13 Feb. 72	34	10 to 11 Feb. 73
9	12 to 14 Mar. 71	22	10 to 12 Mar. 72	35	9 to 11 Mar. 73
10	9 to 11 Apr. 71	23	7 to 8 Apr. 72	36	7 and 14 Apr. 73
11	9 to 11 May 71	24	6 to 7 May 72	37	7 to 8 May 73
12	2 to 4 June 71	25	4 to 6 June 71	38	7 to 8 June 73
13	30 June to 2 July 71	26	30 June to 1 July 72	39	6 to 7 July 73

The typical broad, gravel-dominated beach prevailed until late fall of 1971 when a 10-foot loss to the dune bluff and loss of all of the beach occurred. As before, the beach recovered by the next survey period. A prominent gravel ridge formed shortly after breakup of the shore ice in the spring of 1972. The ridge prevailed for at least 2 months, serving as some protection to the backshore zone. Heavy mineral concentrations during late June indicated that there was erosion to the beach followed by rapid recovery.

Little change to the beach was noted during the summer and fall of 1972, with the exception of some erosion in September and December. There was recovery in the intervening period. The most significant period was in the spring of 1973 when 11 feet of the terrace eroded. There was nearly complete erosion of the beach during June 1973.

b. Profile Site 2. A steep sand bluff extends over 250 feet above the lake immediately behind the active beach. Much of the slope is covered with vegetation which acts to stabilize the slope even though it is at or in excess of the angle of repose.

At the initiation of the study (August 1970), there was a rather broad beach of sorted sand. During September 1970, much erosion of the beach occurred which caused the usual concentration of heavy minerals in the backshore area. Although the beach recovered well during the following fall, the heavy mineral sand remained. More beach erosion and heavy mineral concentration occurred during July 1971.

There was no significant change to the beach through the fall of the second year although a slight narrowing was evident in December 1971. The heavy mineral concentrate which prevailed at this site for the previous 18 months was covered with a veneer of sand during the spring of 1972. Maximum beach width was reached during the June 1972 survey, followed by beach erosion during July.

Nearly the entire beach eroded during September 1972, causing the first erosion to the bluff behind the beach. There was a pronounced accretion of the beach during October and some bluff retreat in November 1972. Following the ice breakup in the spring of 1973, erosion again was severe with more bluff retreat. Recovery occurred in June, followed by more beach erosion during July 1973.

c. Profile Site 3. This site is adjacent to Bar Lake in Manistee County. The beach is bounded by a terrace of beach and dune sands that rises 10 to 20 feet above the lake. Sediment is mostly sand with scattered fine gravel occasionally present in the plunge zone only.

At the initiation of the study there was a broad beach; however, erosion occurred during September 1970. Most of the beach recovered before the next survey. This was followed by minor beach erosion during December and terrace erosion in January. Erosion to the beach occurred after ice breakup the following early spring. Although recovery provided a well-

developed beach, erosion in June 1971 left the beach narrow throughout the early summer.

Some beach accretion occurred in September 1971, followed by general erosion through the fall with both the beach and the terrace experiencing retreat. Accretion during the spring of 1972 provided a fairly wide beach but this was followed by erosion during June of that year.

The summer of 1972 was a period of gradual accretion. It was followed by a long-term period of erosion during the fall, with 16 feet of the terrace removed. More terrace erosion occurred after ice breakup in 1973. The beach accreted in March 1973 but then eroded during June 1973.

d. Profile Site 4. This site is about 300 yards south of the lighthouse and the recently abandoned U.S. Coast Guard station at Big Sable Point. An arcuate steel seawall protects the installation; waves reflecting from the seawall may exert some influence on the beach at the profile site. The coastal area is composed of extensive dunes which are somewhat active and contain blowouts. Grass and small bushes cover most of the dunes which rise up to 30 feet above lake level.

At the start of the surveying program there was a broad beach. Modest erosion occurred in September 1970, but there was no noticeable change in beach width until shortly after the breakup of shore ice in the spring of 1971. From April to June 1971, beach erosion was severe and the face of the dune eroded 2 feet.

Although there was no appreciable accretion during the following summer, the period of September to December was one of marked beach growth; the dune face retreated 12 feet during this period. This further emphasized the rapid rate of beach recovery in that each of the surveys in September, October, and November 1971 had shown a net beach growth from the previous survey. This means that in each of the 4-week intervals there were both beach and terrace erosion followed by rapid beach accretion which resulted in net growth. Shortly after the breakup of shore ice, the beach was almost totally removed. This situation, coupled with erosion to the dune, characterized the spring of 1972. The largest, single-period slope retreat for any location (20 feet) was recorded here on the June 1972 survey.

Because of the severe erosion, virtually no beach existed through the late summer of 1972. A modest increase in beach width, which was partly attributed to the fall decrease in lake level, occurred in October and November 1972. There was a marked net growth of the beach throughout the spring and summer of 1973.

e. Profile Site 5. The coastal area at this site is dominated by high bluffs which rise about 40 feet above the lake; however, this particular profile line crosses a sand terrace. There is abundant evidence of an extremely thin sand and gravel prism over the Pleistocene glacial drift. After periods of erosion the coarse cobble lag accumulations, which are

typically present over till, were the total beach material. Glacial till was also exposed in the plunge zone.

A moderately well developed beach was present at the beginning of the study. By September 1970, most of the beach was eroded with a concentration of heavy minerals in the backshore zone. There was some beach accretion by the next survey, followed by terrace erosion totaling 18 feet of recession during November and December 1970. A demonstration of the rapid recovery of the active beach was evident between the October and November 1970 surveys. Although there was erosion to the terrace, the beach was wider in November than in October. This indicated that the beach and terrace eroded after the October survey, and there was sufficient beach recovery to cause a net increase in beach width from October to November. By December 1970, the beach was comprised of coarse cobbles only. This was also true following ice breakup in the spring. After terrace erosion and modest beach accretion in May 1971, there was no appreciable change in beach geometry.

Erosion caused an overall decrease in the beach width in August but there was accretion and the presence of a ridge and runnel feature in September 1971. Throughout the fall of 1971 there was continued accretion which resulted in the beach becoming wider than it was at the beginning of the study. After the shore-ice breakup in the spring of 1972, there was a 5-month period of modest erosion with some terrace retreat.

Erosion accelerated in September 1972, continuing until November when modest accretion was apparent. More beach erosion followed with the terrace receding 4 feet. Erosion in March and April occurred after the ice breakup, followed by accretion; little change occurred from then to the termination of the survey.

f. Profile Site 6. This site is located just north of the lighthouse at Little Sable Point, near a large area of active dunes adjacent to Silver Lake. The dunes in the immediate vicinity of the profile are fairly well stabilized by grass and poplar trees. Accretion was occurring in the foredunes, and there was almost 1 foot of sand accumulation around the marker stake during the course of study.

At the beginning of the study, this site had the broadest and best-developed beach of all those surveyed. There was some minor beach erosion in September 1970, but it was followed by accretion. No appreciable changes took place until minor beach erosion occurred in July 1971.

The second year was similar in that minor erosion occurred in September 1971. No other appreciable change was noted during the year except for some beach accretion following the spring breakup of shore ice.

Appreciable erosion of the beach preceded the August 1972 survey and continued through September when 12 feet of recession occurred at the base of the dune. More dune retreat was noted in December 1972. The beach was narrow throughout the fall and after the breakup of shore ice. More erosion

to the beach and dune occurred in the spring. By the end of the study there was only a steep foreshore beach with lag concentrates of heavy minerals and an adjacent bluff about 6 feet high. Most of the erosion occurred during the final study year.

g. Profile Site 7. Bluffs of glacial drift predominate near this site. At the base of the bluffs, a sand terrace nearly 100 feet wide with a small eolian ridge near its lakeward margin was present at the beginning of the study. However, this ridge eroded during the course of the study.

A narrow beach was also present at the beginning of the study. There was significant beach and terrace erosion before the September 1970 survey, followed by accretion during October and further erosion in late fall. After some initial accretion in the spring, erosion continued through the end of the first study year.

There was some beach accretion in August 1971, followed by terrace erosion in November and December. Although there was some additional beach accretion in the spring, erosion occurred in May and June 1972, followed by the welding of a ridge during July.

September and October of the third year were the times of most appreciable beach erosion. There was little change through the remainder of the fall and through the spring of 1973, except for a modest accretion of the beach just after the breakup of shore ice. Erosion prevailed in the summer of 1973, leaving essentially no beach at the end of the study.

h. Profile Site 8. Rather steep bluffs of Pleistocene lake sands dominate the coast at this site although dunes are present locally. The profile is about 150 feet south of the paved road between Duck Lake and Lake Michigan. Because of the threat of erosion to the road, large concrete slabs have been dumped on the slope adjacent to the road. This protection protrudes beyond the natural coast and undoubtedly has some effect on the processes at the site.

A moderately well developed beach with a steep foreshore was present at the start of the survey, and heavy mineral concentrations were abundant in the backshore area. There was considerable erosion in September 1970, followed by a modest recovery of the beach and subsequent beach erosion. After the ice breakup, erosion occurred throughout most of the spring of 1971, except for some accretion in May. The summer was a period of modest erosion.

From August 1971 until the formation of shore ice, there was an alternation of accretion and erosion. After the ice breakup, erosion continued throughout the rest of the study year.

Erosion was significant in fall of 1972 with terrace retreat in October and December, interrupted by some accretion in November. Terrace erosion occurred in late spring.

i. Profile Site 9. This site is adjacent to a broad foredune terrace which fronts large, stabilized dunes at the P.J. Hoffmaster State Park south of Muskegon, Michigan. The modern age of this terrace can be estimated by the presence of a 1953 Ford automobile incorporated in it.

A broad beach was present at the first survey; some accretion was noted in October, followed by erosion during late fall. After ice breakup there was a modest accretion in April; however, by the next survey (May 1971) nearly all of the beach had eroded. There was also some terrace erosion during May and June.

As the second year began there was little change until erosion occurred in November and December 1971. After spring melting, the beach was well developed, with accretion occurring in April and June. However, erosion in July 1972 reduced the beach considerably.

Severe beach erosion occurred in September 1972, leaving the beach narrow through the fall. The terrace retreated 11 feet just before ice formation. More erosion occurred in the spring and summer of 1973. At the end of the study there was essentially no beach present.

j. Profile Site 10. The coast in this area, which is almost completely developed with residences, is comprised of dunes stabilized by mature vegetation. At the beginning of the study, the dunes extended to the beach, but after the first 2 years recession of the dune exposed a bluff of glacial till which underlies the dunes.

A narrow beach was present at the beginning of the study. Beach and bluff erosion occurred throughout the fall of 1970, with 23 feet of bluff retreat before ice formation. A small amount of apparent accretion followed ice breakup in the spring but beach erosion prevailed in June and July 1971.

Beach erosion dominated at the beginning of the second year, leaving essentially no beach by the end of August 1971. Continued bluff retreat during the fall exposed a clay-till bluff which had been covered by beach and dune sands. The bluff rises about 8 feet above lake level and is capped by sand dunes. Slight beach accretion followed ice breakup but by the end of June there was no beach remaining.

Only a small beach accreted during the summer of 1972, and it was removed in September. The same accretion-erosion situation occurred in late fall. A small beach was present immediately after ice breakup in 1973, but it was eroded after 1 month. There was about 1 foot of water at the base of the till bluff throughout the remainder of the year.

k. Profile Site 11. This site is located in one of the most heavily populated coastal areas of eastern Lake Michigan. Trees and dwellings occupy the crest of a dune ridge that rises 30 to 40 feet above the lake surface. At the initiation of the study, a narrow foredune terrace had developed locally. This was also the site of a detailed time-series study during the summer of 1970 (Davis and Fox 1971; Fox and Davis, 1971).

A wide beach was present at the start of the surveys, but beach erosion occurred during August 1970. An alternation of monthly accretion and erosion preceded ice formation. After ice breakup, the beach appeared the same as it had during initiation of the study. There was minor erosion in June and essentially no change throughout the remainder of the first year.

Although the beach remained the same through the summer, significant beach erosion occurred about 500 feet to the north such that the profile line crossed a marked beach protuberance. No significant change occurred through the fall, but there was apparent accretion during December, followed by minor bluff erosion before ice formation. Minor accretion followed ice breakup but erosion prevailed throughout the rest of the year, resulting in almost no beach.

After modest accretion in August 1972 there was slight erosion. Much bluff recession occurred in late fall. Accretion followed ice breakup in the spring and there was erosion again in June 1973.

l. Profile Site 12. This profile is located near a marked change in coastal geology. There are high bluffs of glacial drift to the south and large, stabilized dunes to the north. A rather broad terrace was present at initiation of the study. Like site 11, this site is highly developed with residences.

A wide, well-developed beach was present during the first survey. Swash marks indicated that the entire beach was covered before the September 1970 survey, but erosion was slight. There was significant beach and terrace erosion in late fall. Modest accretion occurred in March 1971, but erosion prevailed in April.

There was little change during the fall of 1971 except for minor erosion in September. Much beach and terrace erosion took place before ice formation, and substantial accretion occurred after the spring ice breakup. This led to a wide beach through the summer.

The fall of the third year was one of continued erosion. Spring of 1973 was a period of net erosion, although there was beach accretion just after shore-ice breakup.

m. Profile Site 13. High clay-till bluffs dominate the coast for several miles in either direction. The active beach abuts against the bluff with no sand terrace. This is the only profile line which is near a small natural barrier to sediment transport, a coastal protuberance composed of Pleistocene till a few hundred yards to the south. This location has been monitored since June 1968 as part of another study (Davis, 1972).

A wide beach present at the beginning of the study remained stable until September 1970 when continued fall beach erosion began. Much accretion followed and then substantial beach erosion.

There was much beach erosion in July 1971 and only slight accretion during the next 2 months. Much reduction in beach width and some terrace erosion preceded ice formation. There was a tremendous amount of accretion during one surveying period in June 1972 which left the beach wide through the summer.

The wide beach prevailed in August 1972, but by the end of September it was nearly gone. A small amount of accretion occurred in November, and accretion continued after melting of shore ice, followed by modest erosion in the late spring and early summer of 1973.

The only erosion to the bluff at this location was a small amount at the toe of the bluff. This limited erosion was partly due to the resistance of the till and partly to the coastal protuberance to the south which aided beach accumulation.

n. Profile Site 14. This site is adjacent to some of the largest dunes on the eastern coast of Lake Michigan with many rising in excess of 150 feet above lake level. The profile is located at the base of a large blowout which had a broad foredune terrace at the beginning of the study. A thick peat bed and lake clays are present near lake level at the base of the terrace. This location has also been monitored since June 1968 (Davis, 1972).

A well-developed beach and a swash bar were present at initiation of the study. Erosion to the beach was rather severe in September 1970 but the following month accretion returned the beach to its original condition. A similar pattern followed during the next 2 months. Modest accretion followed the spring ice breakup, and then some erosion occurred. Little change took place during the remainder of the year.

Modest erosion during July 1971 was followed by 2 months of accretion. Fairly severe beach erosion occurred during the late fall storm period although some accretion was noted in December 1971. More erosion followed after shore-ice breakup and in June 1972. Stability then prevailed through the end of the year. Although there was much activity on the beach, no erosion occurred on the terrace during the first 2 years of study.

After initial accretion in September 1972, erosion was prevalent throughout the late summer and fall with recession of the terrace also significant. Rills in the backshore were prominent in November 1972, thus indicating that till or lake clays which perch water were close to the beach surface. Much erosion occurred after shore-ice breakup with 21 feet of terrace being removed, exposing an additional thick peat bed about 20 feet above lake level. Beach accretion followed in June and July 1973.

o. Profile Site 15. This site is located in an area of fairly steep, high bluffs of glacial drift. The tops of these bluffs, which rise about 40 feet above lake level, are covered with mature vegetation and occupied by residential developments. No sand terrace was present during the study period.

A modest beach was present at the beginning of the study. After an initial period of beach erosion, some accretion occurred in October 1970, followed by more erosion up until shore-ice formation. After the shore-ice breakup, the beach was similar to that at the start of the study, and a swash bar was present. Growth of the beach continued although there was some erosion in May and July of the first year.

Late summer of 1971 was characterized by modest erosion followed by accretion. Erosion was dominant during the late fall high-energy period, and minor beach erosion and bluff recession followed the melting of shore ice. This continued through the remainder of the second year.

Early fall was a period of much beach erosion although there was accretion in the usually high-energy month of November 1972. The spring of 1973 was marked by erosion to the extent that by June there was no beach and about 1 foot of water at the base of the bluff. Slumping and some recession of the bluff also occurred in this period.

p. Profile Site 16. Although small vegetated dunes occupy the coast adjacent to the profile at this site, there are extensive bluffs of glacial drift which begin less than 1 mile north of the profile site. A narrow and somewhat discontinuous foredune terrace was present in this area until the summer of 1969. This location was also the site of a time-series study (Fox and Davis, 1970a). During that study an extremely severe summer storm was monitored (Fox and Davis, 1970b) which provided some insight to beach and coastal erosion.

A fairly well developed beach with heavy minerals in the backshore area was present at the beginning of the study. After initial beach erosion there was much accretion in October 1970. Severe storms in November 1970 drastically reduced the beach, but by the next month it was back to its original condition although the dune had eroded 4 feet. After ice melting there was accretion, followed by minor terrace erosion in May and July 1971.

Late summer and fall of 1971 were periods of modest erosion. Accretion followed the breakup of shore ice. The summer of 1972 was characterized by stability.

September 1972 was a period of much beach erosion, followed by slight accretion. The beach remained rather narrow immediately after ice breakup, followed by much accretion during the next few months. The beach was much wider at the end of the study than at its initiation.

q. Profile Site 17. The coastal area at this site is comprised of high bluffs of glacial till with sand terraces between the bluffs and the active beach. About 1 mile to the north, dunes dominate the coast, continuing for several miles. Nearshore profiles were surveyed at this site the summer of 1963, a time of extremely low lake level (Davis and McGeary, 1965).

A wide beach existed at the start of the study. Modest erosion in September was followed by terrace recession in November and December. Most of the beach was removed during storms in early November 1970. Accretion and erosion occurred during the 2 months following ice breakup in the spring. The same pattern was then repeated through July.

Accretion in January of the second year was followed by some erosion. Terrace erosion preceded ice formation. Erosion dominated during the spring although some increase in beach width occurred in June 1972.

Accretion continued in August 1972, but there was much erosion in the fall (20 feet of terrace recession). After the early shore-ice breakup there was no beach and 1 foot of water at the base of the till bluff. This situation prevailed until a small beach developed in late spring of 1973.

2. Discussion of Profile Changes.

Although it is difficult to generalize the beach profile changes, there are several factors which are apparent when looking at the entire spectrum of time and location. As discussed in previous reports (Davis, 1972; Davis, Fingleton, and Pritchett, 1975), there is a general absence of recognizable patterns of erosion and accretion (Tables 5 and 6). This was particularly true during the first 2 years of study, but during the third year, erosion prevailed nearly everywhere (Table 5; Fig. 6). In comparing data from Table 5 and Figure 6 with data on Table 6, note that Table 5 and Figure 6 report bluff or terrace recession only, but Table 6 includes added information on beach erosion or accretion. Reevaluation and rounding off of data that appear in Table 4 of Davis, Fingleton, and Pritchett (1975) result in slight changes of that data on Table 5 of this report, totaling 7 feet.

The ease with which the beach can change is shown by the large temporal and spatial variations in beach conditions. During the 4-week sampling intervals there was time for a wide range of coastal conditions so that only net changes were recorded during the site visits. These net changes may reflect gradual processes or short-term and intense storm activity. In some situations there was intervening storm activity which caused terrace or bluff erosion, even though the net beach change during the 4-week survey period was one of accretion. This is an indication of the rapid changes that can take place on beaches.

A compilation of beach changes at each location over the 3 study years demonstrates the aforementioned variability (Table 5). Only 4 of 38 surveys showed spatial uniformity in changes over a 4-week interval. (There were 39 surveys in all but the first survey does not provide changes from a previous condition.) In one of these (Table 5, survey No. 13, July 1971), there were only 7 of the 17 sites that showed a change, and all exhibited beach erosion. Survey numbers 3 and 29 were during the same month of the year (September), and showed beach erosion at sites 12 and 17, respectively. The fourth case was survey number 32, in December 1972, when only 10 sites were not bound by shore ice, and all but 2 of the 10 showed erosion. Thus,

Table 5. Bluff and terrace recession, eastern Lake Michigan, 1970-73

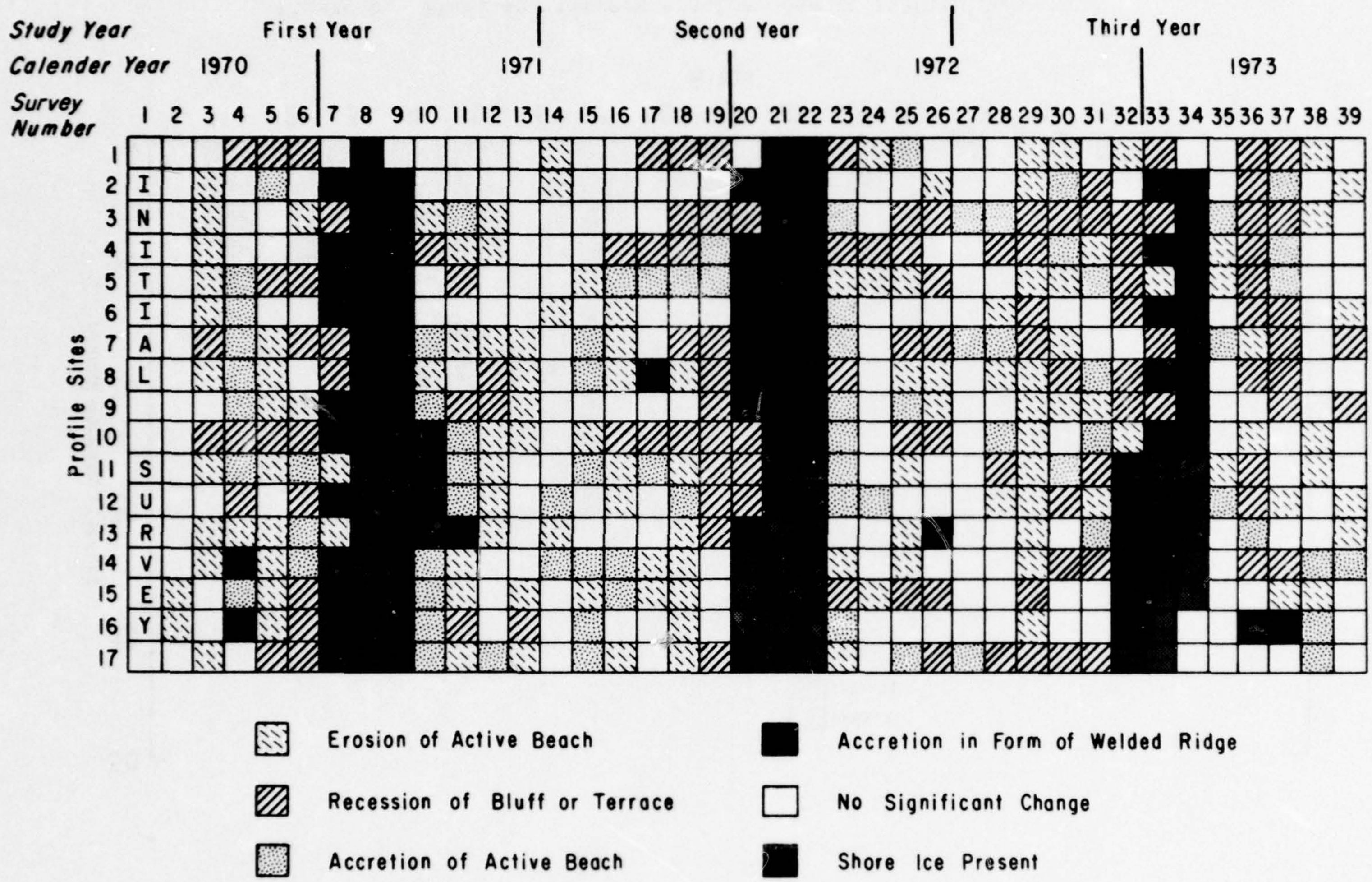
Profile site	Orientation	First year													
		5 Aug.	29 Aug.	27 Sept.	25 Oct.	22 Nov.	20 Dec.	17 Jan.	13 Feb.	13 Mar.	11 Apr.	14 May	4 June	2 July	Total
1	N. 13°E.				2	1	4	0			0	0			7
2	N.5°E.					0					0				0
3	N.27°E.			0	0	0	0	4			0	0	0	0	4
4	N.7°E.		0	0	0	0	0				2	0	0		2
5	N.7°W.					7	11				0	1		0	19
6	N.7°E.			0			0	0			0	0			0
7	N.18°W.			8		0	8	10				0	4	0	30
8	N.24°W.				0		0	1			0	0	1		2
9	N.25°W.						0	0				3	3	0	6
10	N.11°W.			3	4	14	2	0							23
11	N.3°E.		0			0	0	0			0				0
12	N.16°E.				2		1	0			0				3
13	N.15°E.						0								0
14	N.25°E.					0		0			0	0			0
15	N.34°E.										0		0	0	0
16	N.28°E.						4					1		1	6
17	N.43°E.		0	0	0	2	1							0	3
	Total	0	0	11	8	24	31	15	0	0	2	5	8	1	
		Second year													
		3 Aug.	28 Aug.	26 Sept.	24 Oct.	20 Nov.	21 Dec.	17 Jan.	13 Feb.	12 Mar.	8 Apr.	7 May	6 June	1 July	Total
1	N.13°E.				1	6	4	0			1	0			12
2	N.5°E.					0					0				0
3	N.27°E.			0	0	1	4	1			0	0	1	1	8
4	N.7°E.		0	7	3	2	0				2	8	20		42
5	N.7°W.					0	0				0	0		1	1
6	N.7°E.			0			0	0			0	0			0
7	N.18°W.			0		1	5	0				0	1	1	8
8	N.24°W.				0		1	0			1	0	0		2
9	N.25°W.						3	0				0	0	0	3
10	N.11°W.			2	2	2	1	1							8
11	N.3°E.		0			0	2	2			0				4
12	N.16°E.				0		8	7			0				15
13	N.15°E.						2								2
14	N.25°E.					0		0			0	0			0
15	N.34°E.										1		1	1	3
16	N.28°E.						0					0		0	0
17	N.43°E.		0	0	0	0	8							2	10
	Total	0	0	9	6	12	38	11	0	0	5	8	23	6	

Table 5. Bluff and terrace recession, eastern Lake Michigan, 1970-73.-Continued

Profile site	Orientation	Third year													
		30 July	26 Aug.	30 Sept.	21 Oct.	19 Nov.	29 Dec.	14 Jan.	11 Feb.	11 Mar.	14 Apr.	8 May	8 June	7 July	Totals
1	N.13°E.				1	0	0	1			6	5			13 32[1]
2	N.5°E.					5					4				9 9
3	N.27°E.			3	1	2	2	8			4	2	0	0	22 34
4	N.7°E.		7	5	0	0	5				1	0	0		18 62
5	N.7°W.					0	4				6	0		0	10 30
6	N.7°E.			12			2	2			5	10			31 31
7	N.18°W.			1		0	0	5				1	0	2	9 47
8	N.24°W.				1		5	0			2	3	0		11 15
9	N.25°W.						6	5				8	0	2	21 30
10	N.11°W.			0	0	0	0	0							0 31
11	N.3°E.		2			9	0	0			3				14 18
12	N.16°E.				8		0	0			7				15 33
13	N.15°E.						0								0 2
14	N.25°E.					5		2			14	7			28 28
15	N.34°E.										4		0	0	4 7
16	N.28°E.						0					0		0	0 6
17	N.43°E.		1	1	10	10	0							0	22 35
	Totals	0	10	22	21	31	24	23	0	0	56	36	0	4	
		0[1]	10	42	35	67	83	49	0	0	63	49	31	11	

[1]Total for 3-year period

Table 6. Dominant coastal changes, eastern Lake Michigan.



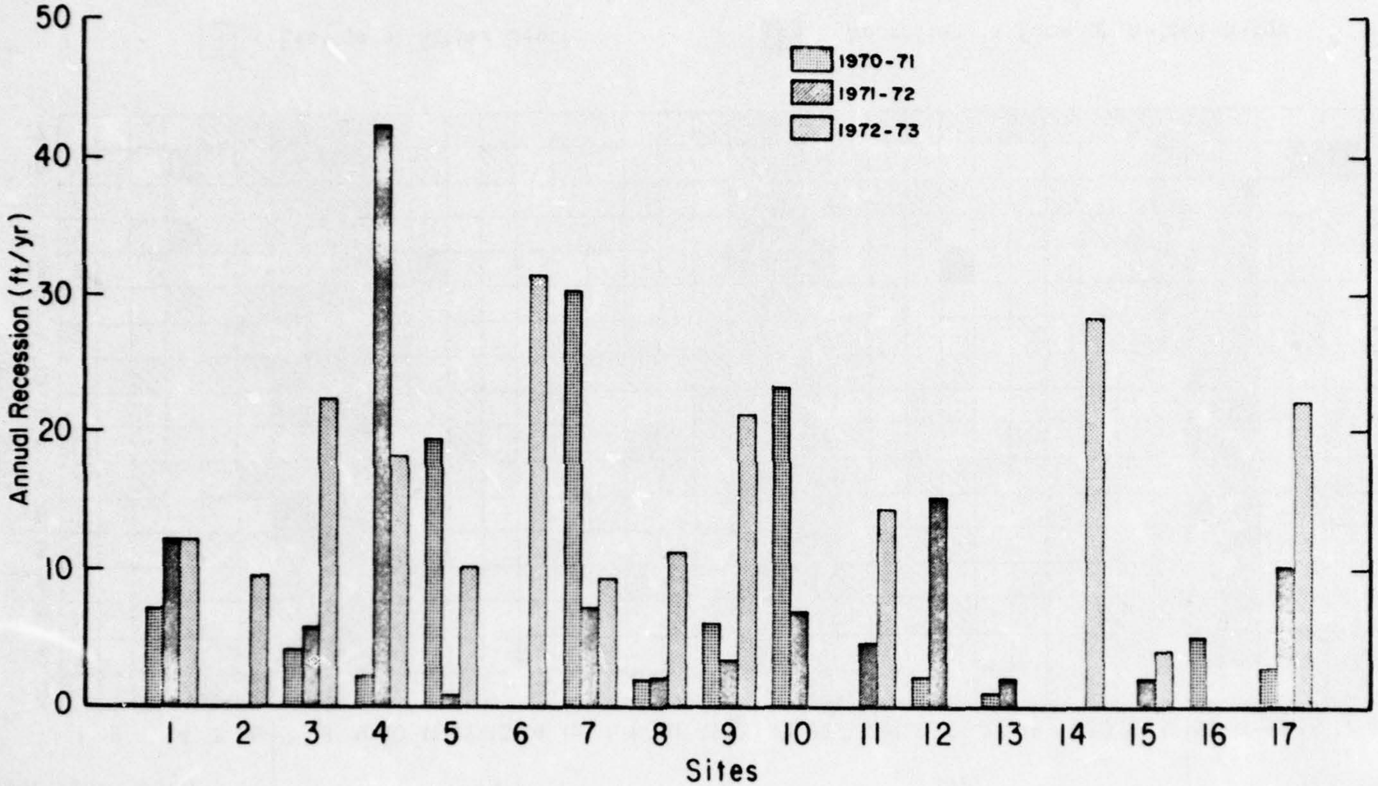


Figure 6. Bluff and terrace erosion, August 1970 to July 1973.

only 4 out of 38 possible surveys showed spatial uniformity and all were periods of erosion. The reason for their occurrence in September is apparent. August or September is generally the time of maximum lake level within the annual cycle. As a result, an early fall storm has an important impact on the coast.

There were times during the study when substantial parts of the eastern Lake Michigan coast were subjected to the same net process (Table 5). During late fall storm periods, beach erosion occurred across large segments of the coast, typically the southern part; e.g., November 1970 and 1971. In December 1970 and 1972, the northern sector experienced erosion. Although less common, the same generalization is also true for beach accretion. In December 1970, sites 11 to 14 experienced a net growth of the beach. A similar situation prevailed during other periods at other sections of the coast.

3. Sediment Budget.

To obtain at least a semiquantitative sediment budget for the sites monitored, the profile changes were determined and converted to sediment volumes (Table 7). These annual changes were calculated above a datum equal to lake level at the start of the study. This differs from the method used to calculate volume changes in Davis, Fingleton, and Pritchett (1975, p. 52). Annual changes in the present report are taken from the profiles plotted at the end of each study year. To obtain sediment volumes, a unit width of 1 foot was used for each profile. *Because of uncertainties* in the surveys the volume rates of erosion are measures of relative rates, and are not reliable estimates of absolute losses.

Figure 7 and Table 6 both indicate the great variability alluded to in previous discussions. Although all sites show a net loss over the 3-year study, there are some which show net accretion in 1-year periods except for the final year during which all sites experienced erosion. In the first year, profile sites 2, 6, and 14 had net accretion as the result of beach growth. Sites 3, 4, 5, 7, and 12 all experienced at least 4 cubic yards per foot of sediment loss. The following year three different sites (5, 13, and 16) showed a net beach growth; sediment of at least 4 cubic yards per foot occurred at sites 1, 3, 4, 15, and 17, the greatest at site 4 (-15 cubic yards per foot). Ten profile sites (1, 3, 4, 6, 9, 11, 12, 14, 15, and 17) lost at least 4 cubic yards per foot of sediment during the final year. Only four sites (2, 8, 13, and 16) lost less than 4 cubic yards per foot during the 3-year period.

VI. AERIAL PHOTOGRAPHY ANALYSIS OF COASTAL CHANGES

A systematic analysis of available aerial photography was used to determine the nature of long-term changes to the coast. Photos are available from 1938 to present although none were found to have been flown between 1938 and 1950. Attempts were made to obtain photos taken at times of low and high lake level to evaluate the long-term effects of this variable.

Table 7. Annual changes in sediment volume at each site.

Sites	Study year ($yd^3/ft/yr$) 1970-71	1971-72	1972-73	Total
1	-1	-5	-8	-14
2	+1	-1	-2	-1
3	-4	-4	-6	-14
4	-6	-15	-18	-39
5	-6	+1	-1	-6
6	+3	-2	-4	-4
7	-6	0	-1	-7
8	0	-1	-1	-2
9	-3	-2	-7	-12
10	-2	-3	0	-5
11	-1	-2	-4	-7
12	-5	-1	-7	-13
13	0	+2	-2	-1
14	+1	-3	-8	-10
15	0	-5	-4	-10
16	-2	+1	-2	-3
17	-1	-5	-7	-13

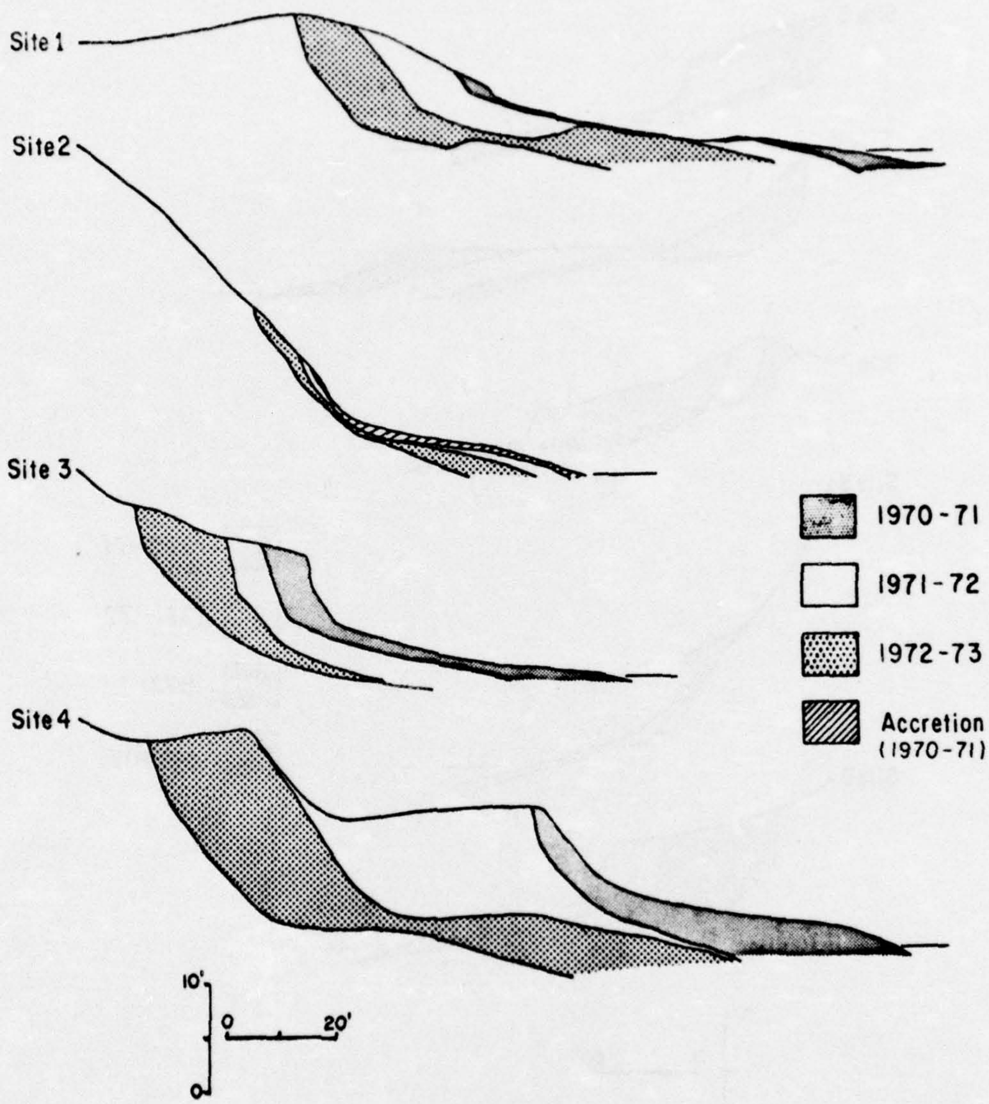


Figure 7. Profiles at each site showing net annual changes. Diagonal heavy lines indicate a net accretion for that study year.

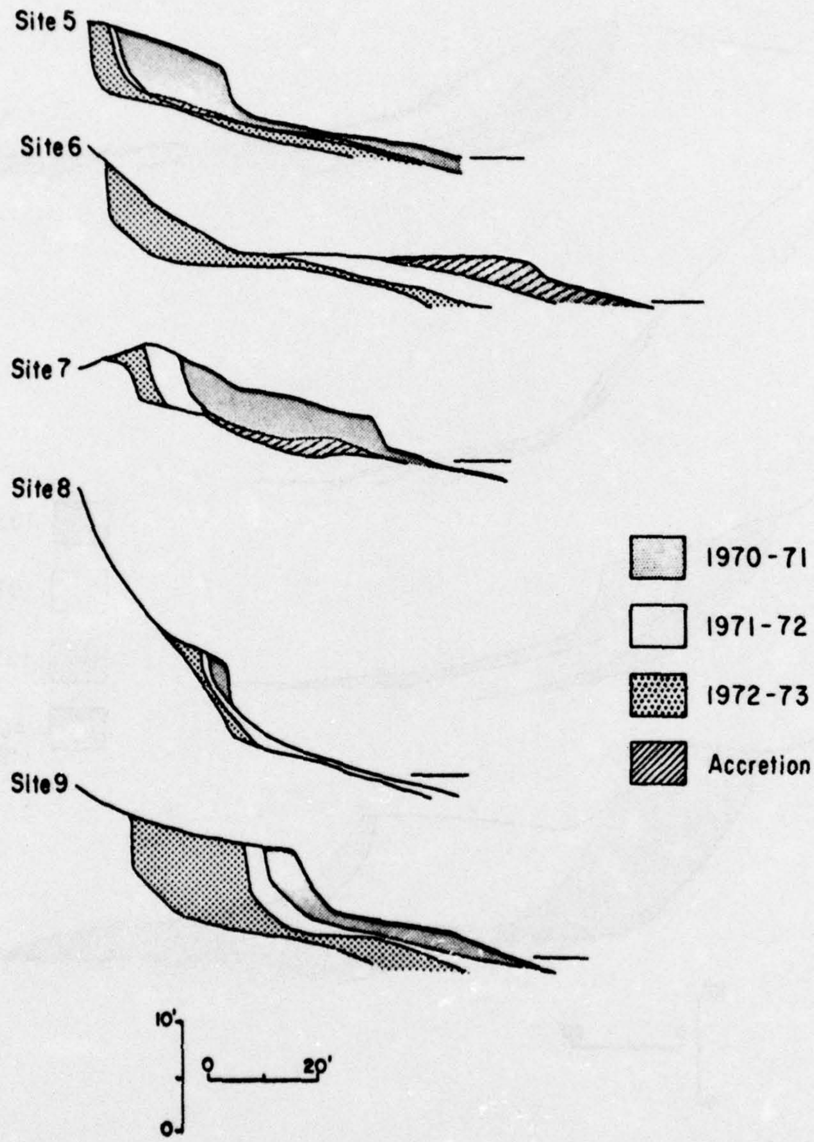


Figure 7. Profiles at each site showing net annual changes. Diagonal heavy lines indicate a net accretion for that study year.-Continued

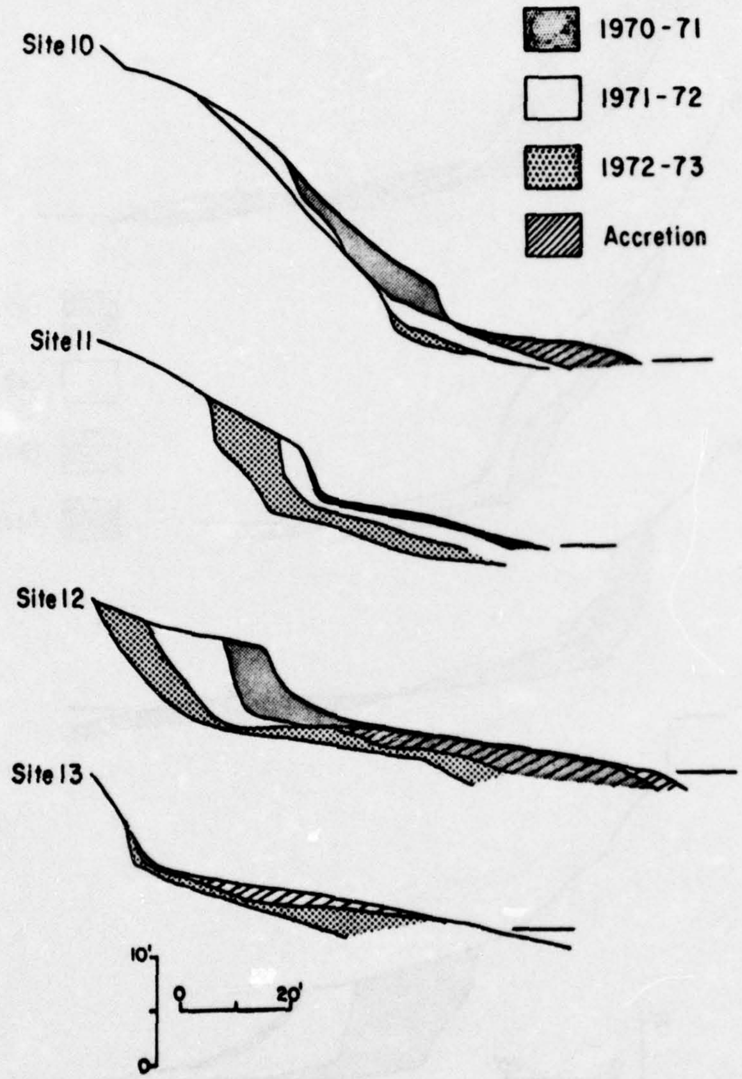


Figure 7. Profiles at each site showing net annual changes. Diagonal heavy lines indicate a net accretion for that study year.-Continued

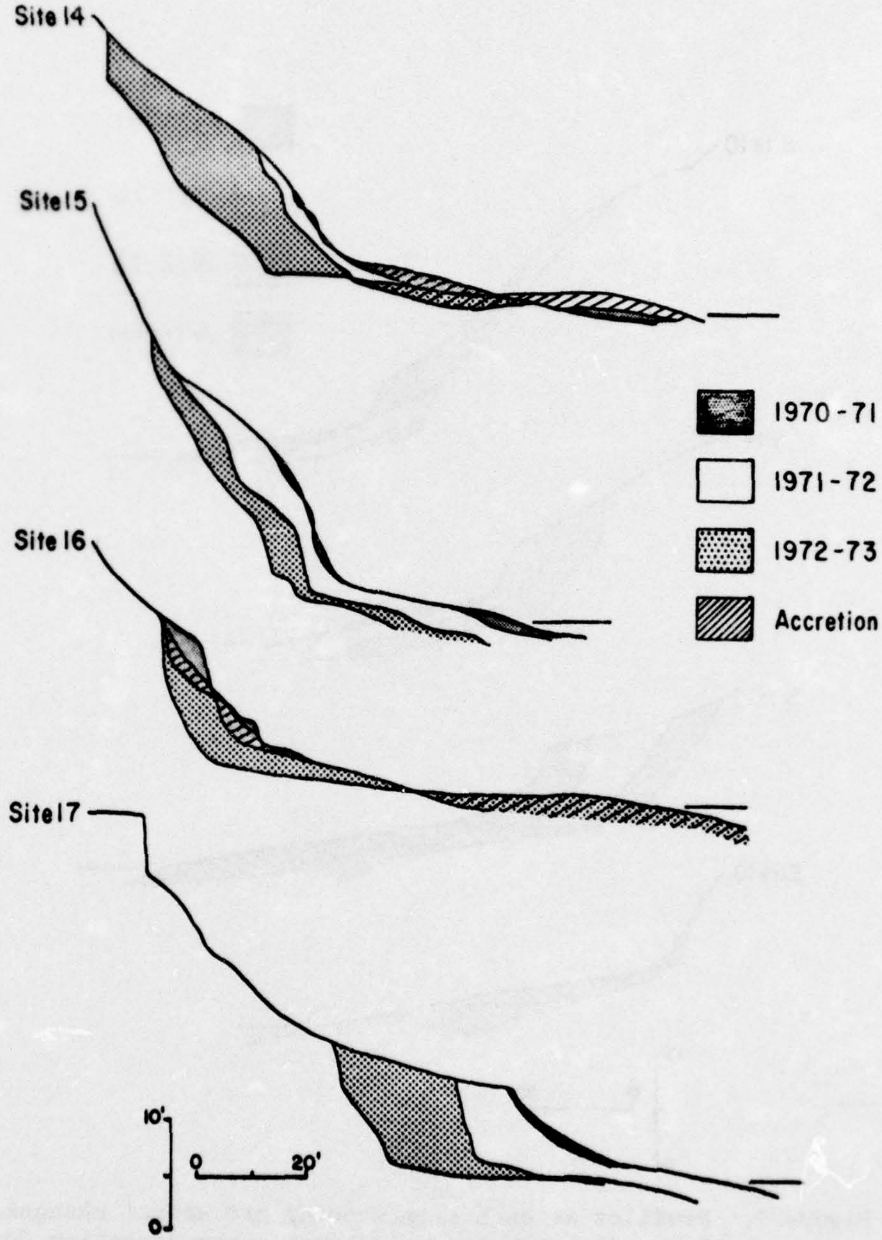


Figure 7. Profiles at each site showing net annual changes. Diagonal heavy lines indicate a net accretion for that study year.-Continued

1. Data Collection.

Reference points were chosen in close proximity to each of the 17 profile sites. The points designated were easily recognizable features that could be seen on all photos of a particular location; e.g., corners of buildings, large trees, or stairways. An effort was also made to choose the points as close to lake level as possible to minimize the parallactic effect due to elevation. Measurements included the horizontal distance from the designated points to the edge of the terrace or bluff, shoreline, and the crest (lightest part) of each bar. All measurements could not be performed on every photo and as mentioned previously, attempts to measure the longshore bar positions proved fruitless. Measurements were scaled by measuring an actual distance in the field and comparing this to the aerial photo. This was accomplished by taking the phocos to the coast and locating features that appeared on the photos.

A Zeiss Aero Sketchmaster was used at maximum magnification to locate reference points and mark points for measurement. Actual measurements were made with a reticle and optical comparator, giving measurements accurate to 0.05 millimeter on the photos.

2. Lake Level During Period of Aerial Photography.

Aerial photos obtained for the study span a fairly broad range of lake level positions. However, it was not possible to obtain photos during some extreme lake level conditions. Figure 8 shows changes in mean annual lake level during the period of photo coverage (1938-72). This represents essentially a complete, but minor cycle in lake level with the photos taken at periods of low level. An abrupt and extreme rise occurred between 1950 and 1952; 1952 had the highest levels to date in this century. There was a steep decline to 1959, then a year of marked increase before falling toward the alltime low level in 1964 (Fig. 8). From this point to the present there has been a rather steep and uniform rise in lake level.

3. Aerial Photo Data.

a. Shoreline. The change in shoreline position is one of the measurements which show a rather predictable and marked change with respect to changes in lake level. The strand-line position was measured from a common reference point for all photos available. From these data, average annual rates of change were calculated for the shoreline position, and plotted at the midpoint between photo dates (Fig. 9). Figure 9 is divided into two parts so the data can be more easily distinguished; the left half of the figure showing results for profile sites 1 to 9 which are in the northern half of the study area. There is some room for error in that the photos were not all flown at the same time of the year. As a result, there may be some effect of annual lake level fluctuations; e.g., photos flown in spring before foliage is abundant are at a time of low lake level; summertime photos are flown during near-peak lake level. This effect of lake level rise on shoreline position will vary with slope of the foreshore, which in turn, depends on the littoral material and perhaps on wave action.

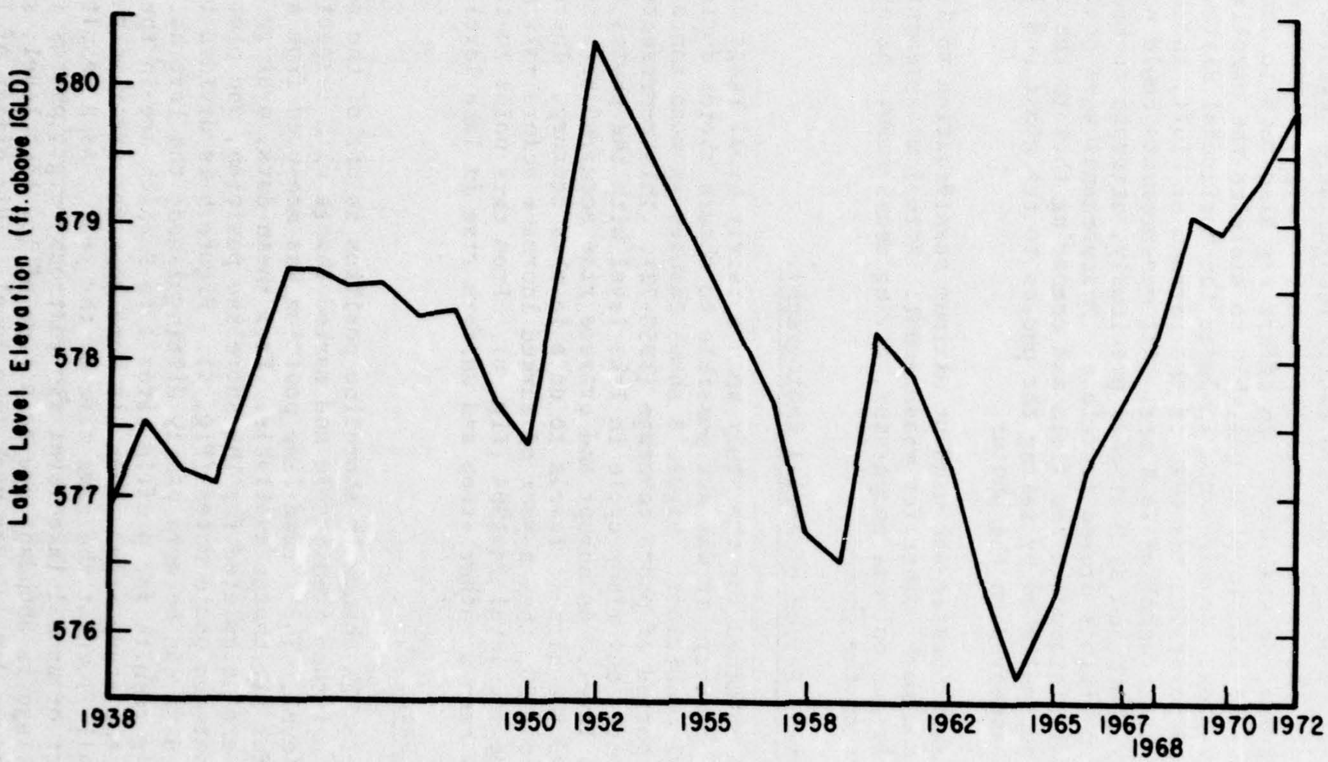


Figure 8. Mean annual lake level during period of aerial photo coverage. Dates indicated on the time scale are the years for which some aerial photos are available.

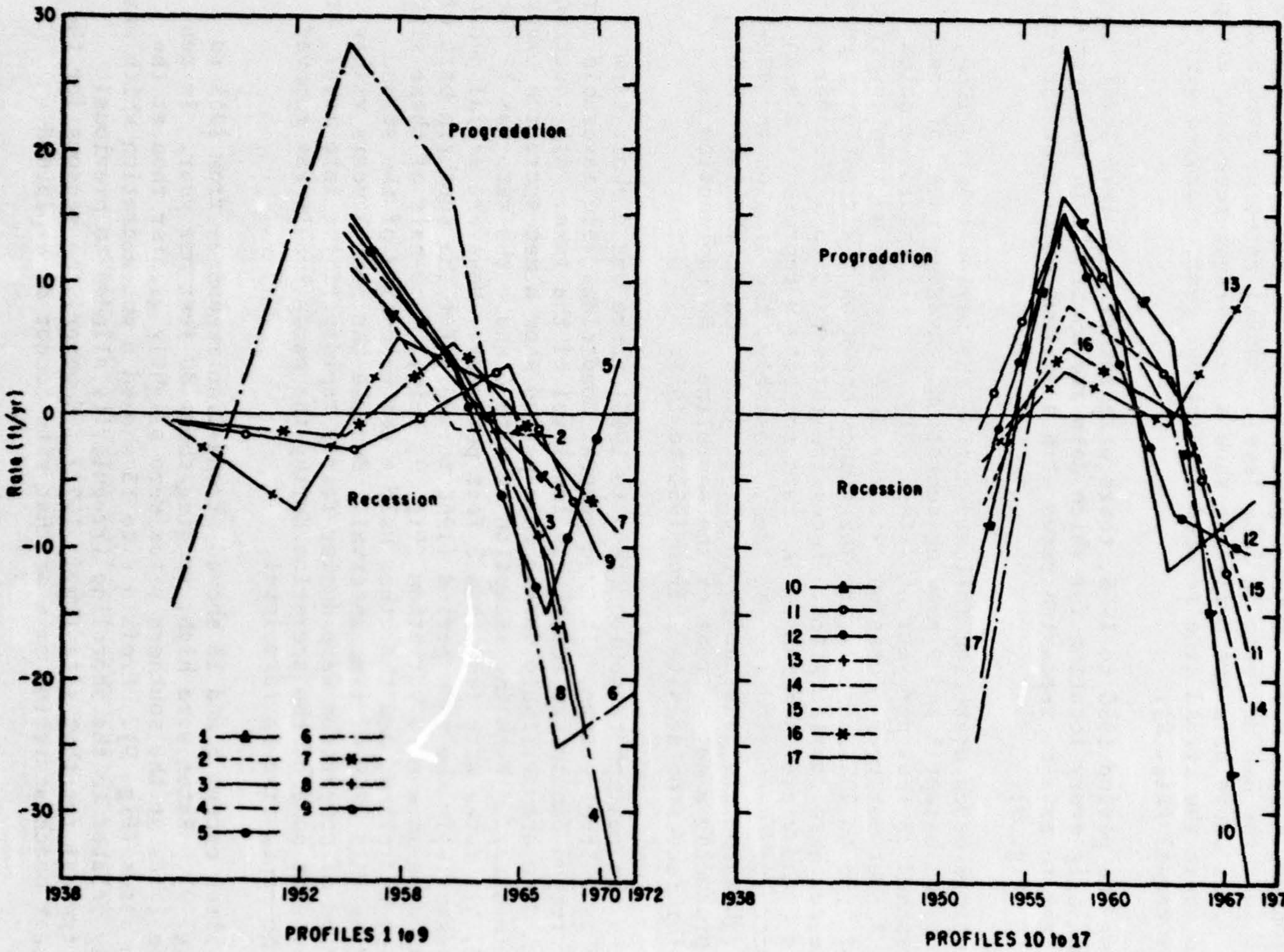


Figure 9. Apparent accretion or recession of strand-line positions (from aerial photos).

The apparent shoreline position may also be affected by the amount of run-up at the time of the aerial photo.

The longest single period between photos (1938-52) represents a period of modest increase and decrease in lake level. Annual rates of change at the four sites where data are available show a very slight recession except at site 6 where the strand line receded 14 feet per year, averaged over the 14-year interval (Fig. 9).

During the period 1950 to 1955, there were rather high lake levels and correspondingly every location for which data are available in the period shows slight to extreme recession rates with a maximum of 25 feet per year at site 14 (Fig. 9).

Widespread beach accretion followed during the period 1952 to 1960, with all sites except 7 and 9 showing accretion. Average rates of beach growth reached 28 feet per year at site 6 (Fig. 9). It should be noted that the 8 feet per year recession rate for site 8 is for a photo coverage period of 1950 to 1955, similar to the trends shown on the right of Figure 9 for the southern profile sites. Recession rates of 2 to 3 feet per year for sites 7 and 9 are anomalous. The rate for site 9 represents a mean annual rate for the period 1950 to 1962. Possibly, the erosion in 1952-53 during high lake level was enough to offset accretion in the late 1950's, thereby producing a net retreat of the shoreline. No explanation is offered for recession at site 7 from 1952 to 1958.

During the next photo period (1958 to 1965) there was a short-term cycle of lake level change, although general conditions were favorable for beach accretion due to the relatively low level of the lake. All locations for which data are available during this period show a net accretion except on profile site 2. With the exception of site 6 where the rate was 17 feet per year, all rates were less than 5 feet per year. However, aerial photos during essentially the same period (1960 to 1967) for the southern part of the study area show more variation (Fig. 9, left). One-half of these sites show a net accretion, and the other half a net recession of the strand line during this 1960-67 time interval. Because the last 3 years within this period of comparison were during fairly rapidly rising lake level, it is likely that some of the accretion during the early 1960's was removed during the rapid rise in lake level.

All sites except 5 and 13 showed strand-line recession from 1965 to 1972 (Fig. 9). Rates were high, ranging about 40 feet per year. In general, the rates at the southern sites were slightly greater than at the northern sites (Fig. 9). Profile site 13 showed a net accretion which was undoubtly related to the shoreline irregularity alluded to previously; this is typical for that site (Davis, 1972). However, the reasons for the significant beach accretion rate at that site cannot be explained.

In general, the pattern shown by the strand-line position from the photos is expected; it moves lakeward during low or decreasing lake level, and landward as lake level increases. This is caused both by the changing

level and the associated erosion. Few changes in strand-line position cannot be explained in this manner.

b. Terrace Bluff. Although somewhat subtle in the topographic expression at some locations, the presence and absence of vegetation are excellent indicators of the lakeward margin of the foredune or sand terrace. At some sites it was impossible to distinguish where the landward extent of the terrace terminated, especially when it was adjacent to low-lying dune areas. It is the lakeward edge of this feature which most authors refer to as the bluff (e.g., Seibel, 1972). The terrace is present throughout most of the eastern coast; where it is absent, recession rates represent the true, steep bluff of Pleistocene glacial drift. However, it is impossible to determine accurate recession rates of the Pleistocene bluffs in many parts of the coast because they are almost always steep and capped by mature trees. As a result, the actual position of the bluff is masked on the photos. In the present study this was the case only at site 15 and to a lesser extent at site 5.

Although data were only available for a few of the sites during the 1940's, all showed no significant changes in the position of the terrace bluff. The northern sites showed both accretion and recession during the period 1952-58, a general decline in lake level (Fig. 8) with the range from accretion of 3 feet per year to recession of 3 feet per year (Fig. 10, left). As expected, the period 1950-55 shows a marked recession of the terrace bluff at the southern sites. Rates ranged from 5 to 13 feet per year (Fig. 10, right). The photo coverage of the southern sites (Fig. 10, right) includes the extremely high levels of 1952 in which is not the case for the northern sites (Fig. 10, left).

During the late 1950's and early 1960's there was either stability or accretion at all sites with the majority showing accretion (Fig. 10, left). Maximum rates were 10 feet per year. This is also to be expected because of the general decline in the lake level toward the alltime low of 1964.

The next period (1965-70) between photo coverage shows mixed changes throughout the east coast of Lake Michigan. Sites 4 and 5 showed accretion between 1965 and 1970; however, the rest of the northern area experienced modest recession with rates less than 5 feet per year (Fig. 10, left). The corresponding period for the southern locations shows similar results (Fig. 10, right). These rates and trends are to be expected because this period is one of rising lake level. The two sites where a significant rate of accretion is indicated (sites 4 and 14) are adjacent to large dune areas, indicating areas of sediment accumulation. It is unlikely that rising lake level would cause recession at these sites until near the peak in the cycle.

All sites showed general recession from 1967 to 1972. Rates were less than 10 feet per year except at site 4 where there was severe erosion in the spring of 1972 (Davis, Fingleton, and Pritchett 1975). The rapid increase in lake level during this period is the primary cause for this general erosion.

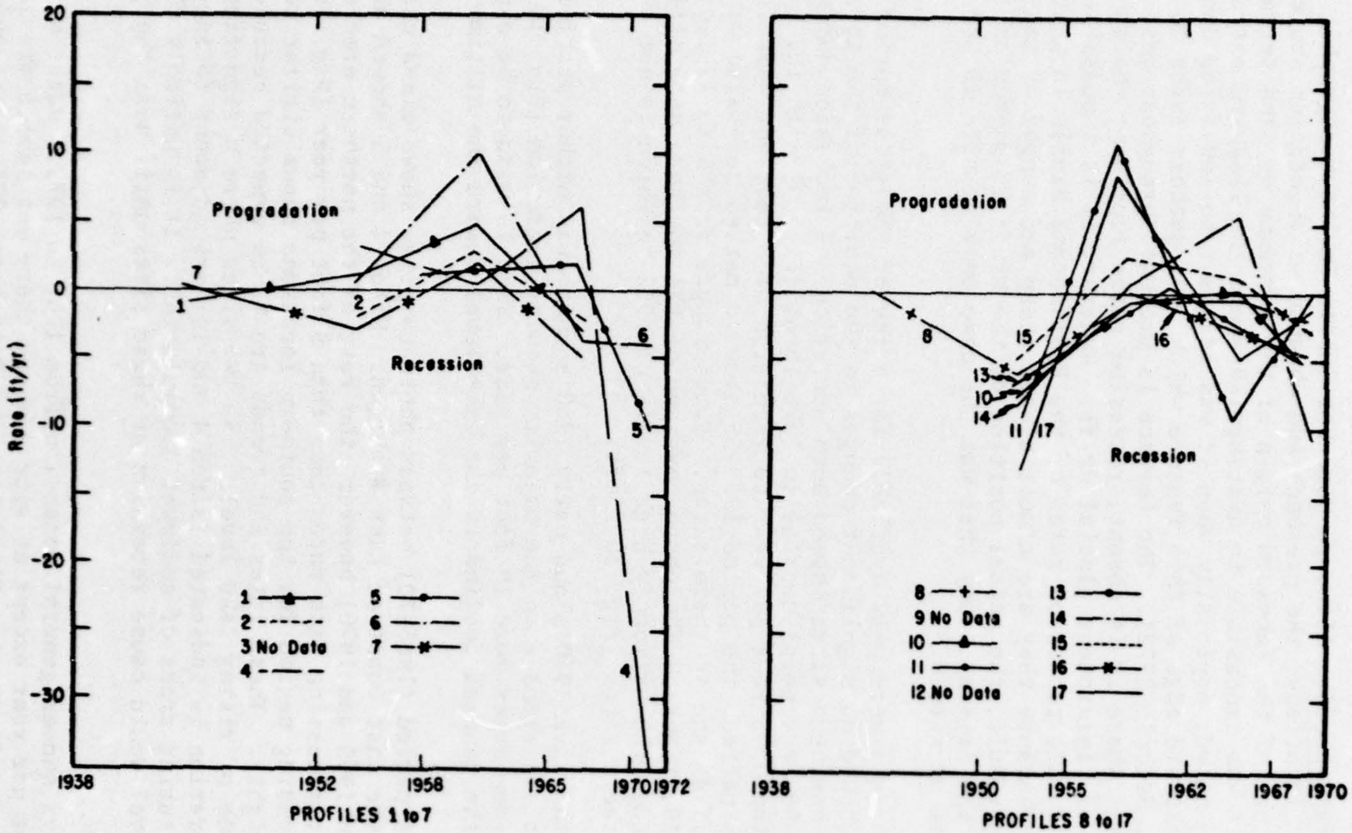


Figure 10. Rate of progradation or recession of terrace-bluff position (from aerial photos).

4. Summary.

Almost no unexpected shoreline or bluff changes were observed on aerial photos. General trends corresponded closely to lake level changes. Most exceptions are explainable in light of geomorphic or geologic location on the coast. Even the rates of change for most sites fall within a fairly narrow range. Extreme rates of both erosion and accretion, e.g., site 6 (Fig. 9, left), are the result of the site location on Little Sable Point, an area of much sediment accumulation. The rates presented are mean annual rates for the time interval involved. To obtain improved information, annual aerial photo coverage would be required.

VII. NEARSHORE BOTTOM PROFILES

One of the variables which may affect coastal processes and sedimentation is the presence of longshore bars which are ubiquitous throughout eastern Lake Michigan (Hands, 1976). These sandbars are of considerable importance in that they are a controlling factor in the amount of energy imparted to the beach during storm conditions. This is due to the refraction and breaking of waves approaching and passing over the longshore bars. As a result, the bar depth and distance from shore to bar are critical factors. The number of bars and their configuration should be of some importance also in controlling the wave and longshore current energy reaching the beach.

There have been a number of studies which have attempted to determine both the details of the topography in the longshore bar and trough zone and the stability of these bars. The first systematic study by Evans (1940) indicated that the bars were fairly stable. This was supported by findings of Davis and McGeary (1965) and Davis and Fox (1971), who were particularly concerned with short-term changes in longshore bars as the result of storms. They found no significant changes caused by storms in four different areas of the eastern Lake Michigan coast. However, it is the present author's opinion that during storm conditions there are changes in the bar and trough profile, but that as storm conditions subside there is a return to the equilibrium state that prevailed before the storm. As a result no significant net changes can be seen after a storm. Data from Berrien County, Michigan, tend to confirm the above hypothesis (Erwin Seibel, personal communication, 1972).

Long-term changes in longshore bar position and bar sediment characteristics were noted in a study by Saylor and Hands (1970) and Hands (1976). They found that as lake level increased in the late 1960's there was a corresponding shoreward migration of the longshore bars. This is in contrast with Evans' (1940) opinion that the bars are left behind as relicts when the lake level increases.

1. Data Collection.

Nearshore profiles were constructed at each of the 17 profile sites from data collected during mid-August 1972, the beginning of the third

study year. The profiles were obtained from fathometer tracings and Emery's (1961) method of stake and horizon profiling.

The basic procedure was to move the boat out from the shore along the profile line until the bar and trough topography had been traversed. This was generally at a depth of about 20 feet and a distance of 1,500 to 2,000 feet from shore. At this point the boat was turned around and a traverse was run toward shore, until depth restrictions prohibited continuing farther (usually at a depth of 3 to 4 feet). Two people on the shore profiled to a depth of 4 to 5 feet to permit construction of a complete profile.

Detailed nearshore bottom profiles are also available from previous studies in this area (Davis, 1964; Davis and Fox, 1971), specifically at sites 11 (1970), 13 (1963), 16 (1969), and 17 (1963). Profile lines reported in Saylor and Hands (1970) are near sites 5, 6, and 7. The profile line at site 5 of this study is identical with profile line 32 of Hands (1976); profile site 6 is a little north of Hands' (1976) number 17, and profile site 7 is just south of Hands' (1976) number 24.

Initially, it was anticipated that data on the location of longshore bars could also be obtained from the long-term aerial photo study. Because of turbid water, wave activity, and reflections from the water surface, there were too few photos from which reliable data could be collected.

2. Nature of the Profiles.

Although the two-bar configuration is prevalent throughout the area, there are locations where one or three bars are present. A shallow, ephemeral bar was also present at nearly one-half of the sites. The *ephemeral bar* was defined as any bar with a crest of 3 feet or less below lake level. This bar was present at eight sites (Table 8) with crests ranging from 2.4 to 3.0 feet deep and 80 to 175 feet from shore. The nature of these bars is such that they may be present or absent at any site during any survey period. However, no evidence for the presence of these ephemeral bars was observed during any survey at sites 1, 10, 12, 13, and 17. Coincidently, these are the beaches that have the coarsest mean grain size. During August 1963 an ephemeral bar was present at site 13 (Davis, 1964).

The first relatively stable longshore bar was present at all profile sites except site 13. The crests of this bar ranged from 3.3 to 8.0 feet in depth and 150 to 525 feet from shore (Table 8; Figs. 11 and 12). At nearly every site this bar was well developed.

The second bar was present at all sites with its crest ranging from 580 to 1,625 feet from shore at depths ranging from 7.6 to 14.5 feet below lake level (Table 8). At five sites there was a third bar present. The crest of all of these fell within a rather narrow distance from shore (1,100 to 1,375 feet) with crest depths ranging from 11.2 to 16.0 feet below lake level.

Table 8. Longshore bar data in feet, August 1972.

Site	Ephemeral bar		First bar		Second bar		Third bar		Distance between bar crests	Depth difference of bar crests
	Distance	Depth	Distance	Depth	Distance	Depth	Distance	Depth		
1	---	---	360	6.0	850	11.8	-----	----	490	5.8
2	80	3.0	300	6.0	800	12.0	-----	----	500	6.0
3	125	3.0	500	7.3	1,450	11.6	-----	----	950	4.3
4	---	---	300	3.3	700	7.7	-----	----	400	4.4
5	---	---	250	4.3	650	9.5	-----	----	400	5.2
6	---	---	250	3.4	600	7.7	1,100	12.2	350	4.3
7	175	2.9	440	6.3	900	11.3	-----	----	460	5.0
8	80	2.4	350	6.0	750	8.3	1,150	15.2	400	2.3
9	140	2.4	440	5.8	1,000	10.0	-----	----	560	4.2
10	---	---	300	5.9	800	10.2	-----	----	500	4.3
11	80	2.5	250	4.1	730	7.6	1,350	17.6	480	3.5
12	---	---	150	3.6	580	8.0	1,200	13.7	430	4.6
13	---	---	---	---	950	12.3	-----	----	-----	---
14	---	---	275	3.7	750	7.6	1,250	11.2	475	3.9
15	100	3.0	400	4.2	1,100	11.0	-----	----	700	6.8
16	100	3.0	300	4.2	850	11.0	1,375	16.0	550	6.8
17	---	---	525	8.0	1,625	14.5	-----	----	1,100	6.5

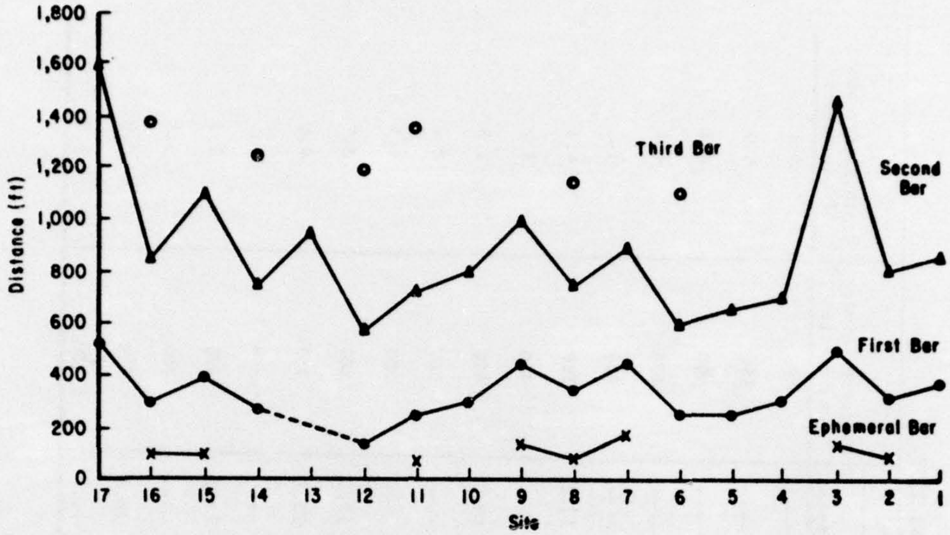


Figure 11. Distance of longshore bar crests from strand line.

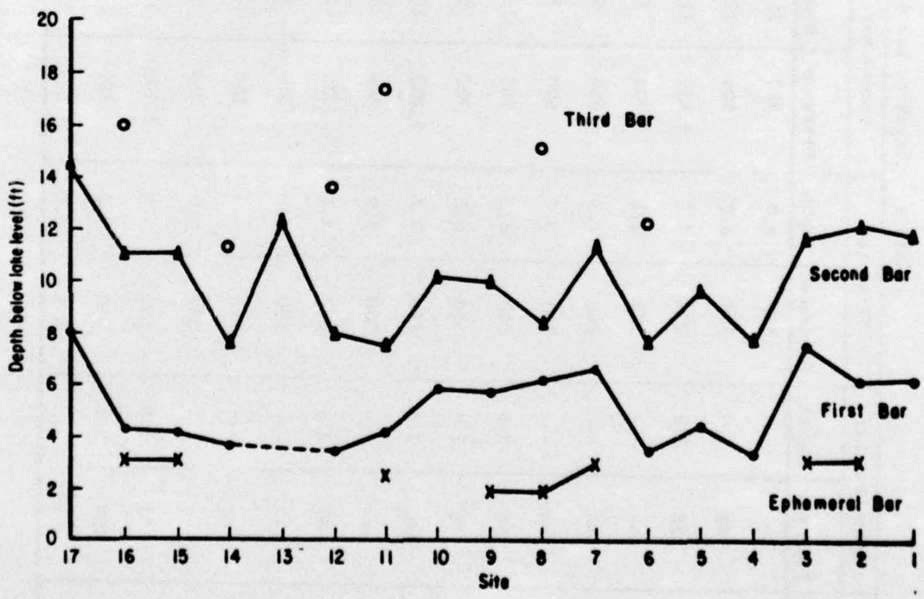


Figure 12. Depth of longshore bar crests.

None of the profile traces showed any flat areas or contained any other indications of a till or boulder pavement between the bars. These conditions were found in some of the profiles surveyed by previous investigators (Davis, 1964; Saylor and Hands, 1970). Boulder pavements were present at site 13 in August 1963 (Davis, 1964).

Site 5, 6, and 7 of this study include the Little Sable Point area where bars were studied more intensively by Hands (1976). As shown in Figures 18, 19, and 20 of Hands (1976), the bars change position or disappear over short distances in this area, suggesting that the first, second, or third bars from sites as widely spaced as in this study are not the same bars from site to site.

3. Effects of Longshore Bars on Beach Changes.

This section examines each of the 17 sites for evidence to support the author's hypothesis that the presence of longshore bars close to shore and at shallow depths acts to protect the shore from erosion. Two assumptions are made concerning the effects of longshore bars on changes that occur in the profile of the beach and adjacent coast. The first assumption concerns the permanence of the profiles. The bar profiles previously described were surveyed at the beginning of the third year (August 1972). In the following discussion it will be assumed that these nearshore profiles, with the exception of the ephemeral bars, prevailed throughout the third year. Based on data by Evans (1940), Davis and McGeary (1965), and Saylor and Hands (1970), this appears to be a reasonable assumption. Presence and location of ephemeral bars were noted when possible during the monthly visits, and will be incorporated in the discussion. The second assumption is that the bars protect the beach and backshore from erosion, other factors being equal.

a. Profile Site 1. This site experienced an increasing amount of volume loss on the profile during the study period. Although there were only 26 cubic feet removed during the first year, the final year had a loss of 222 cubic feet. An ephemeral bar was not observed during the entire study period. The depths of the two bars are 1 foot or more greater than the mean for all sites, and the distance of the first bar is slightly greater than the mean (Table 6). In addition, the depth difference between bar crests is 1 foot above the mean. These parameters and the relatively steep, inner nearshore profile permit a relatively high amount of wave energy to reach the beach.

b. Profile Site 2. Very little loss of sediment was recorded at this site with the maximum being 42 cubic feet during the final year. Although the mean depth of the "permanent" bars is in excess of the mean for all sites, the distance of the bar crests from the shore is slightly below the mean. More importantly, ephemeral bars are typical at this site and the profile immediately adjacent to the strand line is gentle. It is assumed that these bars reduce the wave energy reaching the beach, the ephemeral bar serving as an effective protection for the coast.

c. Profile Site 3. A rather large amount of sediment was removed from this profile during each of the study years, culminating with the loss of 153 cubic feet during the third year. Although an ephemeral bar was present when the nearshore profiles were surveyed, the bar is uncommon at this site. The two permanent bars were also deeper than the mean and considerably farther from shore than at all sites with the exception of site 17 (Table 6). Consequently, less wave energy was absorbed by each of the sandbars and there was more distance over which waves could rebuild after initial breaking on each of the permanent bars. The result was a high amount of wave energy imparted on the beach.

d. Profile Site 4. The profile at this site experienced the greatest loss (492 cubic feet) of all profiles during the third year. Longshore bar data collected during August 1972 indicate that much wave energy should be dissipated before reaching the beach. Beach profile data and observations during site visits show the summer as the typical period of accretion at this site. Net longshore transport in the area is to the north, and the location of this profile site is just to the south of a seawall which surrounds the Big Sable Point lighthouse and provides for sediment accumulation during this time of year. Consequently, the nearshore profile was probably more shallow during the data collection period than during high-energy periods of late fall and early spring.

The above explanation is primarily conjecture. Another factor leading to high erosion rates at site 4 is the presence of the vertical seawall mentioned above. This wall has evidently been scoured at its base. During times of high wave energy there is reflection and refraction of waves from the wall concentrating energy near the profile site. These conditions are unique for the study sites and are interpreted as being important contributors to the rapid erosion at site 4.

e. Profile Site 5. There was little loss of sediment (39.5 cubic feet) at site 5 during 1972-73. Although ephemeral bars are not present at the site, the two permanent longshore bars are both shallow and close to shore (Table 6). The net result is that relatively little wave energy is allowed to reach the beach.

f. Profile Site 6. This profile gained sediment (68.5 cubic feet) during the first year and lost essentially the same volume the following year. All of this change was restricted to the active beach zone. In the third year, 115 cubic feet of sediment was lost (Table 5), the majority of which was within the active beach zone.

The August 1972 nearshore profile displayed longshore bars that were both shallow and relatively close to shore (Table 6). Such a profile would be expected to provide sufficient protection to prevent erosion of the coastal area. This was actually the case until the late spring and early summer in 1973 when there was erosion at the base of the dune behind the beach. A change in the nearshore profile subsequent to the August 1972 survey is the logical explanation for this erosion although no data are available to substantiate this hypothesis.

g. Profile Site 7. Essentially no loss of sediment occurred during either of the last 2 years; however, there was a considerable loss during 1970-71. Although the distance and depth of each permanent longshore bar are slightly greater than the mean, ephemeral bars are typical at this site. The effect of these bars appears to be paramount in protecting the coast from high wave energy.

h. Profile Site 8. There was no significant loss of sediment from the profile at this site. A total of 55.5 cubic feet was lost over the 3-year period with only 16.5 cubic feet during the last year. Although an ephemeral bar was present during the August 1972 nearshore survey, such bars were not typical at that site. A twofold explanation is offered for the lack of erosion at this site. The second permanent bar is relatively close to shore and almost 2 feet shallower than the mean. In addition, the profile is located just south of a concrete slab seawall which shelters the profiles from waves coming from the north and serves as a site of sediment accumulation for material transported to the north by waves approaching from the south. Unlike the structure at site 4, this protective structure is quite open so that there is a minimal reflection of wave energy.

i. Profile Site 9. The loss of almost 200 cubic feet of sediment from this profile during 1972-73 places this location among the most severely eroded during that period. Nearshore profile data collected in August 1972 indicate that the coast at this site should have been well protected. An ephemeral bar was typically present at this site, and the permanent bars were near mean values for depth and distance. Apparently, there was considerable change in the profile during high wave energy periods or other factors not apparent from the data caused this erosion.

j. Profile Site 10. Erosion at this site was the least (9 cubic feet) during 1972-73 of all sites surveyed. Ephemeral bars were not present and the permanent bars were close to the mean in depth. They were somewhat closer to the beach than mean values; however, this is not considered significant in itself. The most effective protection afforded the coast at this site is the tough and resistant clay till which comprises the bluffs. There was essentially no beach throughout the 1972-73 study year; waves were imported directly on the till bluffs with no appreciable effect.

k. Profile Site 11. This site is one of the most puzzling of all those monitored. More than 100 cubic feet of sediment was lost from the profile although the August 1972 nearshore survey indicated excellent protection by the longshore bars. An ephemeral bar was present which is common at this site. The depth of the first bar was 1 foot less than the mean; the second bar was 15 feet less. All of this suggests that much of the wave energy should be dissipated before reaching the beach.

During July 1970, nearshore profiles were surveyed across the same traverse at site 11 as part of another study (Davis and Fox, 1971). A total of four profiles was surveyed during the study. At that time the first permanent bar was more than 100 feet farther from shore and had a crest 1 foot deeper than in August 1972. The second bar was about the same

distance from shore but had a crest 2.5 feet deeper. This indicates that the longshore bars do change. Therefore, it is possible that the August 1972 profile was subsequently modified, thereby permitting more wave energy to reach the coast and cause erosion.

l. Profile Site 12. Much erosion occurred at this site during 1972-73. Nearly 200 cubic feet was lost from the profile (Table 6). Longshore bar data indicate that there should be little wave energy reaching the beach. Bars are much shallower and closer to shore than mean values. Only the steep profile lakeward of the beach is conducive to erosion. However, no substantiated explanation can be offered for the extensive erosion at this site. The possibility of changes in nearshore profile must be considered.

m. Profile Site 13. On the basis of the nearshore profile, it would be expected that this site is subjected to severe erosion. There is only one longshore bar present and it is more than 12 feet deep and 950 feet from shore. Consequently, it provides little protection for the beach. However, only 59.5 cubic feet of sediment was removed during the third year and a net of only 16.5 cubic feet was lost during the entire 3-year period. Essentially all changes were to the active beach.

The primary reason for erosion being minimal is in the location of the profile just to the north of a protuberance in the coastline. Net longshore transport is to the south, and thus much sediment accumulates just north of this protuberance as it would adjacent to a groin. Even if waves reach the till bluffs behind the active beach, there is essentially no erosion due to the resistant nature of the clay till.

n. Profile Site 14. As with profiles at sites 11 and 12, the profile at this site experienced much erosion (202.5 cubic feet) although the nearshore profile apparently provided good protection. Bars were shallower and closer to shore than mean values and ephemeral bars were common at this site. There is no reasonable explanation for the erosion at this site other than the possibility of a change in the profile.

o. Profile Site 15. Erosion was moderate at this site with a loss of 112.5 cubic feet of sediment during the final year. Although an ephemeral bar was present during the August 1972 profile, it is not typical. The first bar is somewhat farther from shore than the mean but it is shallower so that the effects of these parameters cancel one another. The second bar is deeper and much farther from shore than the mean. The overall effect of this on the beach is the ability of waves to rebuild over a broader area and thus import more energy to the beach.

The beach at this site is narrow, and even during minor storms waves attack the base of the clayey bluff. The clay till is soft and almost quick due to a very high moisture content. Erosion to the toe of the bluff results in mass wasting and much loss of material from the profile.

p. Profile Site 16. Erosion at this site was only 62.5 cubic feet of sediment, largely from the active beach. The longshore bars were less than

mean distances from shore; the first bar was less than mean depth and the second was 1 foot more than the mean. Location and depths of bars were much like that observed the summer of 1969 (Davis and Fox, 1971). Ephemeral bars are fairly common and the beach was quite wide. All of these were contributing factors in preventing waves from attacking the adjacent dunes and keeping erosion restricted to the beach.

q. Profile Site 17. This is one of the most severely eroded sites; 190 cubic feet of sediment was lost. The nearshore profile provides adequate data to explain this erosion. The slope adjacent to the beach is relatively steep and both permanent bars are the deepest and farthest from shore of all the study sites (Table 6). There was little to impair wave energy from reaching the shore and removing sediment.

VIII. BEACH SEDIMENTS

Beach sediments were collected and analyzed for textural parameters in conjunction with the profile surveys. Samples were collected during each site visit to determine if there were any patterns (spatial or temporal) to the distribution of beach textures. Foreshore sediments were also collected to test the validity of the grain-size slope relationships described by Bascom (1964) and Shepard (1972).

1. Collection and Analysis of Sediments.

Samples were collected from the backshore and foreshore at each site during all visits except when ice cover was so thick that the beach surface could not be reached. Only surface samples of the upper few millimeters were collected to approximate collecting a single sedimentation unit. Only sand samples were taken; gravel was avoided on mixed beaches, and if the beach was all gravel no sample was collected. Also, the sample was collected from undisturbed positions on the profile traverse. Approximately 50 grams of sediment was collected, placed in a waterproof plastic bag, and labeled.

In the laboratory each sample was ovendried and split with an Otto Microsplitter to a 12- to 15-gram sample. About one-half of this amount was introduced into the Benthos Rapid Sediment Analyzer which plots a cumulative distribution curve for the sample. Two samples were run initially; if they were similar, the first one was analyzed; however, if not, a third sample was analyzed and mean values from all three were used.

Mean grain size, sorting, and skewness were calculated by a graphic method using 16th, 50th, and 84th percentiles.

2. Textural Nature of Beach Sediments.

A great deal of time and effort was devoted to collecting and analyzing beach sediments to determine if there were spatial trends in sediment characteristics (primarily size and composition) along the 17 sites, or if there was a correlation between beach material characteristics and erosion. No trends or correlation were found.

Generally, beach sediments from the eastern coast of Lake Michigan are well-sorted, medium sands. However, there is a tendency for each site to have its own peculiar sediment texture. This texture does not vary appreciably with time except during the time of protection or cover by shore ice. Typically, shore ice and the sampling difficulties associated with it yielded a poorer sorted beach sand as compared to the same site during periods of open water. This is partly due to ice-push activity in the foreshore which mixes sedimentation units, and also due to sediment incorporated in the ice settling down on the beach as melting occurs on the beach proper. This takes place before breakup of the ice ridges when the beach is still in a zero-energy condition.

Because sediment parameters were described in previous reports for the first 2 years of the study (Fingleton, 1973; Davis, Fingleton, and Pritchett, 1975), and there were no deviations during the third year, only a general summary is presented in this report.

Gravel, including cobbles, was abundant at sites 1 and 5, and there was commonly a fair amount of gravel at site 16. Sites 5 and 16 are near Pleistocene till which would provide a source; however, site 1 is on a point (Point Betsie) which contains widespread dune development. Coarse gravel and cobbles which dominate this beach are probably reworked from a Pleistocene source lakeward of the beach. Although gravel is not typical on the beach at site 13, it is common just lakeward of the plunge zone. This site is also adjacent to bluffs of Pleistocene till.

Nearly all beaches had scattered pebbles or rows of pebbles during most visits. Notable exceptions were sites 4, 6, 9, and 11. All of these sites are in areas of dune development and the northern two (4 and 6) are on Big Sable Point and Little Sable Point which are areas of sediment accumulation. These two sites are among those with relatively fine grained sand. There are three sites (12, 13, and 17) which typically contain a large quantity of granules or very fine gravel. As a result, they are the coarsest of the beaches in the study. The sites are located in areas where a Pleistocene till source is adjacent or nearby.

There are easily recognizable local factors which control or contribute the textural characteristics at each of the beaches, with the exception of the cobbles at site 1. Backshore sands are somewhat finer grained and better sorted than foreshore sands which is to be expected because of the combination of wind effects and swash dynamics.

The dynamic and erosional nature of the beaches along eastern Lake Michigan coupled with the tremendously heterogenous source of sediment provided by Pleistocene drift obscures any size-slope relationship described by Bascom (1951) and Shepard (1972) that might exist. All beaches studied are not stable and consequently plots of grain size versus slope show tremendous scatter (Davis, 1972; Fingleton, 1973).

Heavy mineral concentrations were evident at many of the beaches, particularly after erosion periods. These lag concentrates were typical of sites 8, 10, and 14, but were never found at sites 6, 12, 13, and 17.

IX. SUMMARY AND CONCLUSIONS

An analysis of the profile changes on the shore of eastern Lake Michigan suggests the following (see also Davis, Fingleton, and Pritchett, 1975, pp. 54-58):

1. There is evidently a critical mean annual lake level beyond which erosion is universal. This level is apparently about 580.0 feet in eastern Lake Michigan. Although beach erosion and adjacent bluff erosion are definitely linked to high lake levels, the lake level plays a passive role, not an active one. Primary evidence of this is the fact that erosion was intermittent during the first 2 years, but erosion was universal in the third year when mean lake level was the highest.

2. Local factors predominate in controlling erosion and accretion during most conditions. Of these factors, the nature of longshore sandbars, composition of the bluff and beach, and coastal configuration appear to be most significant. Local embayments or protuberances in the shoreline are significant factors. Clayey till is relatively resistant to wave attack.

3. Available aerial photos suggest that long-term changes are tied closely to lake level conditions. Photos indicate that sand terraces behind the active beach have remarkable capabilities of regeneration during periods of low lake level. Large terraces can apparently form in a decade or two.

4. Storms are the dominant force, with the bulk of the coastal erosion occurring in only a small percentage of the total elapsed time. As few as two or three major storms per year can account for the majority of the erosion. However, there is extremely rapid recovery of beaches between storms. Only a week or two is necessary in most instances.

5. There are obvious seasonal variations in the coastal processes. Late fall and early spring are the periods of highest erosion due to the increased frequency of storms. Winter ice cover affords excellent protection for the coast against these storms.

6. Beach sediments are closely related to adjacent sources and are generally well-sorted, medium sand. No correlation was found between the nature of the sediments and coastal erosion.

7. Based on this report, it appears that longshore bars do have some effect on coastal erosion, but the cause and effect relation is not clear.

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